Atomic Energy Control Board
P.O. Box 1046
Ottawa, Canada
K1P 5S9

Commission de contrôle de l'énergie atomique
C.P. 1046
Ottawa, Canada
K1P 5S9

INFO-0221

AN EVALUATION OF HYDROGEOLOGIC DATA OF CRYSTALLINE ROCK SYSTEMS

by

K.G. Raven and D.W. Lafleur
INTERA Technologies

A research report prepared for the
Atomic Energy Control Board
Ottawa, Canada

December 1986

Canada

Research report

ABSTRACT

This report presents a detailed review of hydrogeologic data collected as part of various research programs investigating fractured crystalline rock around the world. Based on the available information describing the test equipment, test methods and analytical techniques, the data have been assessed in terms of their reliability and representativeness, and likely error ranges have been assigned. The data reviewed include both hydrogeologic parameters, such as permeability, storage coefficient components (principally porosity), and fracture characteristic data.

RÉSUMÉ

Dans le présent rapport, nous examinons en détail les données hydrogéologiques recueillies dans le cadre de divers programmes de recherche portant sur les formations de roches cristallines fracturées qui existent dans le monde. À partir des informations disponibles portant sur les installations et les méthodes d'essais et sur les techniques analytiques, nous avons évalué la fiabilité et la représentativité des données et déterminé des fourchettes d'erreurs vraisemblables. Les données comprennent à la fois des paramètres hydrogéologiques tels que la perméabilité et les composantes du coefficient de stockage (surtout la porosité), et des données sur les caractéristiques des fractures.

DISCLAIMER

The Atomic Energy Control Board is not responsible for the accuracy of the statements made or opinions expressed in this publication and neither the Board nor the authors assume liability with respect to any damage or loss incurred as a result of the use made of the information contained in this publication.

INTERA

TABLE OF CONTENTS

		Page
ABSTRACT		i
LIST OF TABLES		iv
LIST OF FIGURES		v
1.	INTRODUCTION	1
1.1	Background	1
1.2	Scope of Work	3
2.	OVERVIEW OF PARAMETERS AND TEST TECHNIQUES	4
2.1	Permeability	4
2.1.1	Injection Tests	4
2.1.2	Transient Pressure-Pulse Tests	8
2.1.3	Transient Well Tests (Constant Discharge)	11
2.2	Specific Storage	12
2.3	Fracture Characteristics	15
3.	EVALUATION OF SITE SPECIFIC DATA	18
3.1	Stripa Mine	18
3.1.1	Permeability	18
3.1.2	Porosity	36
3.1.3	Fracture Characteristics	37
3.2	Swedish Sites	42
3.2.1	Permeability	42
3.2.2	Porosity	52
3.2.3	Fracture Characteristics	53
3.3	Finnish Sites	54
3.3.1	Permeability	54
3.3.2	Porosity	57
3.3.3	Fracture Characteristics	58
3.4	Nevada Test Site	58
3.4.1	Permeability	58
3.4.2	Porosity	60
3.4.3	Fracture Characteristics	60
3.5	Colorado School of Mines - OCRD Room	62
3.5.1	Permeability	62
3.5.2	Porosity	64
3.5.3	Fracture Characteristics	64

TABLE OF CONTENTS

		Page
3.6	Savannah River Plant Site	65
3.6.1	Permeability	65
3.6.2	Porosity	67
3.6.3	Fracture Characteristics	67
3.7	Oracle Site	68
3.7.1	Permeability	68
3.7.2	Porosity	75
3.7.3	Fracture Characteristics	77
3.8	Basalt Waste Isolation Program	78
3.8.1	Permeability	78
3.8.2	Porosity	81
3.8.3	Fracture Characteristics	81
3.9	AECL's Underground Research Laboratory	82
3.9.1	Permeability	82
3.9.2	Porosity	84
3.9.3	Fracture Characteristics	84
3.10	Atikokan Research Area	86
3.10.1	Permeability	86
3.10.2	Porosity	88
3.10.3	Fracture Characteristics	88
3.11	Chalk River Research Area	90
3.11.1	Permeability	90
3.11.2	Porosity	93
3.11.3	Fracture Characteristics	94
3.12	Whiteshell Research Area	96
3.12.1	Permeability	96
3.12.2	Porosity	97
3.12.3	Fracture Characteristics	98
3.13	Miscellaneous Sites	99
3.13.1	Permeability	99
3.13.2	Porosity	106
3.13.3	Fracture Characteristics	107
4.	SUMMARY AND CONCLUSIONS	108
4.1	Permeability	108
4.2	Specific Storage	110
4.3	Fracture Characteristics	112
REFERENCES		113
GLOSSARY		128

LIST OF TABLES

Page

Table 3.1 Flow Rate Measuring Ranges for Borehole Hydraulic Test Program at Stripa (from Gale, 1981).....20

LIST OF FIGURES

Page

Figure 2.1 Schematic pressure (P) and temperature (T) profiles in the rock on completion of drilling an interval (from Pickens et al., 1986).....9

Figure 3.1 Permeability versus fracture frequency for all HG and R boreholes (after Gale et al., 1982a).....23

Figure 3.2 Permeability versus depth from injection tests in SBH-1 (after Gale et al., 1982a).....24

Figure 3.3 Pulse pressure (ΔP) resulting from imposed displacement volume (ΔV) (after Forster and Gale, 1981b).....27

Figure 3.4 Hydraulic conductivity versus depth for borehole DBh V1 (after Olkiewiez et al., 1978).....29

Figure 3.5 Log-normalized pressure decay versus decay time for a fractured sample of Stripa granite (after Forster and Gale, 1980).....33

Figure 3.6 Comparison between values of hydraulic conductivity determined from the formula by Moye and from transient testing (after Carlsson et al., 1979).....43

Figure 3.7 Hydraulic conductivity from single packer measurements and corresponding value from double packer measurements. Curves are shown indicating leakages corresponding to hydraulic conductivities of 10^{-8} m/s and 10^{-9} m/s in double packer measurements (after Almen et al., 1981).....46

Figure 3.8 Calculated hydraulic conductivity versus depth with a confidence interval of 98% for the rock mass at Fjallveden assuming three-dimensional groundwater flow (after Carlsson et al., 1984a).....49

Figure 3.9 The mean hydraulic conductivities of the drill-holes in which the water loss was measured, plotted against the vertical depth of respective drill-hole below the rock surface (after Carlsson and Olsson, 1977b).....51

LIST OF FIGURES (cont'd)

Page

Figure 3.10 General performance of the borehole hydraulic test program in three steps: Phase 1 (packer sealing, Phase 2 (water injection) and Phase 3 (pressure fall-off) (after Almen and Persson, 1984).....55

Figure 3.11 Comparison between hydraulic conductivities determined by pressure-slug tests and steady-state analyses of injection tests (after Hsieh et al., 1983).....71

Figure 3.12 Directional hydraulic conductivity ellipsoid fitted by ordinary least squares; (a-c) Vertical cross-sections of fitted ellipsoid along planes of test series A, B and C; (d) Oblique view of vertical cross sections oriented in three dimensions; (e) Oblique view of fitted ellipsoid (after Hsieh et al., 1985).....74

Figure 3.13 Guidelines for application range of test methods for test zones at the Hanford site (after Rockwell, 1982).....79

Figure 3.14 Histogram of the distribution of the common logarithm of equivalent rock mass hydraulic conductivity, K_{erm}, determined from packer tests completed from 0 to 75 m depth at the East Bull Lake and Chalk River research areas (after Raven et al., 1986).....101

Figure 3.15 Flow rate per unit head ($Q/\Delta H$) profiles for boreholes EBL-1 and EBL-2 determined from 1983 packer tests and 1984 PIP tests. The test data are plotted as the negative common logarithm (p) of $Q/\Delta H$ expressed as m^2/s (after Raven et al., 1986)....102

1. INTRODUCTION

1.1 BACKGROUND

The principal disposal concept for most high level nuclear waste programs is the isolation of wastes by placing them deep in bedrock. Virtually all nuclear waste isolation programs are required to demonstrate the feasibility of their disposal plan. This demonstration is frequently termed a performance assessment and involves evaluating the impact that the construction and operation of a nuclear waste repository would have on the environment, in general, and man, in particular. The most likely mechanism by which radioactive material could reach the biosphere is by the dissolution and subsequent leaching of the radioactive waste inventory by groundwater and the subsequent movement of these dissolved isotopes through the groundwater system until they are discharged at surface. To assess the risk posed to the human population through the construction of such a facility, it is essential that the flow of groundwater and movement of solute through the formations that provide the isolation capability be understood.

In Canada, the search for a suitable site has centred on crystalline rock masses, more specifically, plutons. The Atomic Energy Control Board (AECB) is the regulatory agency charged with the responsibility of reviewing and approving licensee applications. It is essential, therefore, that the AECB have a good understanding of the hydrogeologic properties that describe groundwater and solute movement through crystalline rock systems. To this end, the AECB has commissioned this study to identify and review hydrogeologic properties pertinent to the flow of groundwater in crystalline rock masses. In addition, this study is responsible for the compilation and evaluation of all data pertaining to the flow of groundwater in crystalline rock systems.

An earlier report prepared by INTERA Technologies Ltd. (as GTC Geologic Testing Consultants Ltd.) identified the groundwater flow parameters relevant to crystalline rock systems and presented a compilation of field values for these parameters. In reviewing the available information describing groundwater flow through crystalline rock masses, it became apparent that the vast majority of the well documented information pertained to a relatively small number of research areas. These sites were typically the object of research being conducted by various governmental agencies or laboratories as part of a nuclear waste disposal program, and included:

- Stripa Mine, Sweden;
- Finnsjon, Kamlunge, Fjallveden, Gidea and Svartboberget Sites, Sweden;
- Olkiluoto, Loviisa and Lavia Sites, Finland;
- The Climax Granite Mine Site, Nevada Test Site;
- Office of Crystalline Repository Development (OCRD) room Colorado School of Mines (CSM), Edgar Mine;
- Savannah River Plant at Aiken, South Carolina;
- Oracle Site, Oracle, Arizona;
- Basalt Waste Isolation Project (BWIP), Hanford, Washington;
- Atomic Energy of Canada Limited's (AECL) Underground Research Laboratory;
- AECL's Atikokan Reseach Area;
- AECL's Chalk River Research Area;
- AECL's Whiteshell Research Area.

In addition to data pertaining to these sites, information from a number of miscellaneous sites and laboratory investigations, such as geothermal sites, university investigations and other nuclear waste isolation programs, has also been included.

1.2 SCOPE OF WORK

This report describes the work performed under the latter portion of the study and basically consists of an evaluation of the reliability of the data collected during the earlier part of the study. More specifically, this report is meant to address the following items:

- assess the suitability of the technique(s) used to collect the data (e.g., is the test capable of measuring the required parameters to the necessary accuracy);

- comment on the validity of any assumptions used in either the test or analytical method and evaluate (where possible) the impact that violations of these assumptions could have on the data;

- provide a critical review of the quality of the collected data with respect to its representativeness and relation to other reported values.

2.0 OVERVIEW OF PARAMETERS AND TEST TECHIQUES

2.1 PERMEABILITY

Permeability data reviewed in this report are determined from laboratory and field tests using a relatively limited number of methods. Because of the similarity of testing methods, a review of the suitability of the methods to collect the basic data and the validity of commonly assumed conditions requisite to the determination of permeability, are assessed in this section. The test methods assessed include:

- steady-state injection/withdrawal tests;
- transient pressure-pulse tests;
- transient well tests (constant discharge).

In addition to these common test methods, several less frequently used test methods are described and evaluated in the context of site-specific investigations. These, for instance, include the ventilation drift permeability experiment at Stripa and transient flow rate injection tests at other Swedish sites.

2.1.1 Injection Tests

The steady-state (constant pressure) injection/withdrawal test is the most commonly used method for evaluating the permeability characteristics of fractured rock. The reliability of the permeability estimated from an injection/withdrawal test is determined principally from the accuracy of the flow rate and pressure measurements. Assuming that flow rate and pressure are accurately measured, injection/withdrawal testing is recognized (Doe and Remer, 1981; Braester and Thunvik, 1984; Bliss and Rushton, 1984) as a generally reliable method for the determination of hydraulic conductivity and permeability of geologic media. The steady-state assumptions of an injection/withdrawal

test result in an equation for the calculation of hydraulic conductivity (K) of general form:

$$K = \frac{Q}{\Delta HL} \cdot C \qquad (2.1)$$

where: Q = steady-state flow rate (L^3T^{-1});

ΔH = imposed steady-state injection/withdrawal hydraulic head (L);

L = test interval length (L); and

C = dimensionless shape constant to account for geometric flow field effects.

Different semi-empirical shape constants have been proposed for porous media analyses (Hvorslev, 1951; Moye, 1967; Dagan, 1978). However, because the difference between most shape factors is not greater than 30% and the factors likely have limited application to fractured media where flow is largely through an unknown network of fractures, concern over the appropriateness of each shape factor is unwarranted. Two commonly used shape factors are those of Hvorslev (1951):

$$C = \frac{1}{2\pi} \ln (r_b/r_w) \qquad (2.2)$$

and Moye (1967):

$$C = \frac{1 + \ln (L/2r_w)}{2\pi} \qquad (2.3)$$

where: L is test interval length, r_w is well radius and r_b is radius to a constant pressure boundary.

Use of equation (2.2) requires an estimate of the radius of test influence, r_b. The radius of influence of an injection/withdrawal test is generally unknown in a single well test and varies with the hydraulic conductivity of the medium and the duration of the test. For a 300 s injection test in an infinitely acting porous medium, the r_b varies between 1 and 10 m for hydraulic conductivities of 10^{-9} to 10^{-6} $m \cdot s^{-1}$ (Doe and Remer, 1981). Selection of a radius of test influence that considers the approximate hydraulic conductivity of the formation and the test duration can result in more accurate estimates of hydraulic conductivity.

Assuming steady flow rate and pressure are accurately measured, the major drawbacks of an injection/withdrawal test relate to the uncertainty in knowing the actual far-field boundary conditions and ignoring the storage in the medium. Doe and Remer, by using an analytical solution for transient radial flow from a borehole, showed that the error associated with these drawbacks and the use of equations (2.1) and (2.2) are generally within a factor of two to three. Doe and Remer concluded that data reported in the literature for crystalline rock K based on steady flow analyses should be considered reliable so long as reasonable values of radii of influence have been used (i.e., 1 - 10 m).

In any injection/withdrawal test program, the largest uncertainties exist in the measurement of flow rates and the determination of equilibrium hydraulic pressures or heads, particularly in low permeability media. The inability to determine low flow rates introduces a lower test limit in hydraulic conductivity measurement. The principal limiting factor in the measurement of very low flow rates is the thermal expansion and contraction of the test fluid caused by the presence of a thermal gradient. Because both the borehole and

surface test environments are rarely isothermal, as a result of geothermal gradients and changes in air temperature, thermal expansion and contraction of the test fluid is inevitable. The theoretical magnitude of this effect, and therefore the limiting range of flow rate measurement, can be evaluated from the thermal expansion properties of the test fluid and an assumed test fluid volume and thermal gradient. The change in fluid volume ΔV due to a change in temperature can be determined from:

$$\Delta V = \alpha V \Delta T \qquad (2.4)$$

where α = the thermal expansivity ($^{\circ}C^{-1}$);
V = the volume of the test interval experiencing a thermal gradient (L^3); and
ΔT = is the change in temperature ($^{\circ}C$).

Using thermal expansivity of ordinary water at 10° and 20°C (data from Weast, 1984) and a conservative estimate of test interval volume (3.0 L), the changes in volume per °C are 0.26 mL and 0.64 mL, respectively. If it is further conservatively assumed that a change in water temperature of only 0.1°C occurs during the flow measurement period of an injection test, then the volume change resulting from thermal effects over the duration of the measurement period would be 0.026 mL (at 10°C) and 0.064 mL (at 20°C). These calculations show that for the assumed conditions, the flow resulting from thermal effects may mask the low flow rate measurement capability provided by the test equipment. Final assessment of the reliability of low flow rate measurements (e.g., less than 0.1 $mL \cdot min^{-1}$) requires measurement of fluid temperature at the surface and downhole within the test interval to accuracies of 0.01°C.

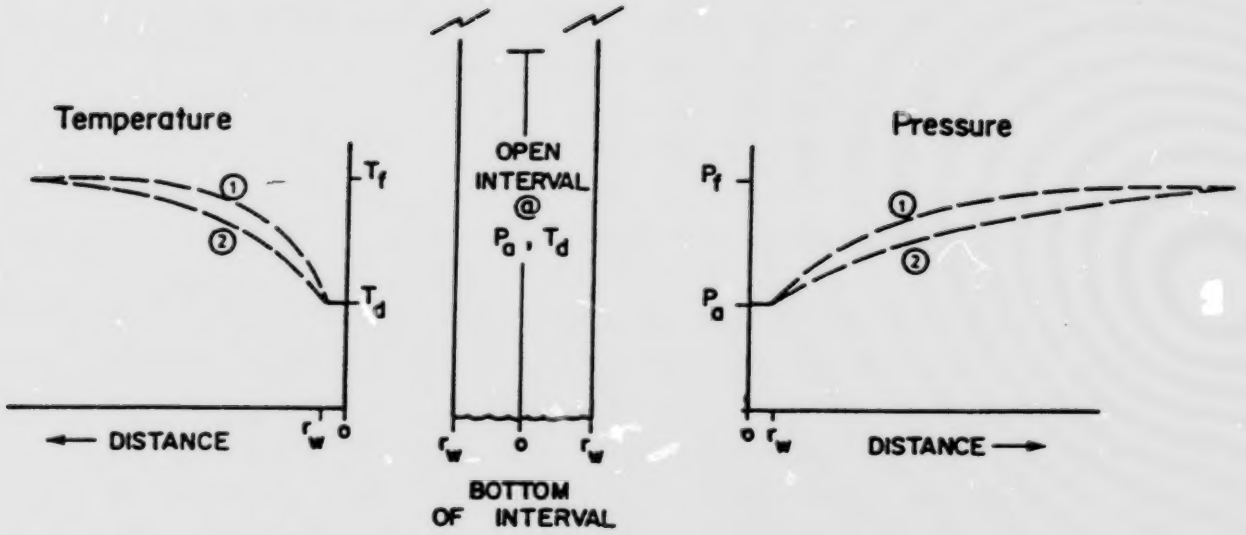
Determination of the applied injection/withdrawal pressures requires a reliable estimate of the equilibrium, or steady-state, pressure for the formation. The reliable estimation of steady-state formation pressures from an open borehole in low permeability rock may

be problematic in the presence of a pressure skin resulting from borehole pressure history effects (Pickens et al., 1986) (Figure 2.1). Borehole pressure history effects are most pronounced in boreholes which have been left open over their entire length for an extended period prior to hydraulic testing. Under these conditions, the open hole fluid pressure is unlikely equal to the true formation pressure and will migrate into the formation, generating an uncertain pressure profile away from the borehole (see Figure 2.1). Under certain conditions, the uncertainty in true formation pressure can be minimized by assuming that the formation pressure is equal to the open borehole pressure and by applying an injection pressure that is substantially larger than the difference between an assumed formation pressure and the open borehole pressure. Under these conditions, the error associated with injection pressure and thus permeability is not expected to exceed the error (factor of two to three) associated with uncertain flow geometry and neglecting medium storativity (the steady-state assumption).

Calculation of medium permeability from hydraulic conductivity determined from field testing further requires reliable estimates of the fluid properties viscosity and density. While fluid temperatures, viscosities and densities are expected to vary with depth and between test sites, the uncertainty associated with the actual fluid properties of viscosity and density are expected to be less than a factor of two.

2.1.2 Transient Pressure-Pulse Tests

In a pressure-pulse transient test, an instantaneous increase in pressure is created within a packer-isolated test interval of a borehole and the decay of the pressure-pulse is monitored in time. The characteristics of the decay curve are a function of several variables



P_a	annulus pressure
P_f	formation (in-situ) pressure
T_f	formation (in-situ) temperature
T_d	drill fluid temperature
①	profile on completion of drilling
②	profile after some period of continued drilling
r_w	radius of borehole

Figure 2.1 Schematic pressure (P) and temperature (T) profiles in the rock on completion of drilling an interval (from Pickens et al., 1986)

including:

- rock permeability and specific storage properties:
- test interval length;
- test interval volume;
- test interval compressibility;
- flow field geometry;
- fluid properties (density, viscosity).

Use of this method to determine rock hydraulic properties requires knowledge of the other variables listed above as well as assumptions of isothermal conditions and uniform initial pressure conditions. The permeability of a homogeneous medium is usually determined from fitting the field data to a curve and by assuming that the remaining variables are known and that the limiting assumptions are met. In low permeability rock (less than 10^{-20} m^2), the assumptions of isothermal conditions and uniform initial pressure conditions may be difficult to achieve and more complex analytical methods that consider temperature and pressure history effects are necessary (Grisak et al., 1985). Irrespective of permeability magnitude, the most uncertain variable in the pressure-pulse test is the compressibility of the test interval. Because the test interval is isolated by flexible instruments such as tubing, packers, "O" ring seals, etc., which may exhibit elastic and possibly plastic behavior, compressibility of the test interval may have order of magnitude uncertainty. Because permeability is determined directly from, among other parameters, the test interval compressibility, this may result in an order of magnitude uncertainty in permeability estimation.

Permeability determined from a transient pressure-pulse test is also influenced by uncertainty in specific storage or storativity of the medium under test. Although storativity may be estimated from type curve fitting, the resultant value is at best only accurate to plus or minus an order of magnitude. However, uncertainty in storage

properties of the medium introduces, in the worst case, an error factor of three and generally less than two in determination of permeability (Black, 1985). Black (1985) also evaluated the error in calculated permeability introduced when a type curve analysis developed for flow in homogeneous porous media was applied to tests conducted in a dual porosity, or fissured, porous media. Bleck concluded that the error involved in such misapplication was unlikely to exceed an overestimation factor of three and, in most cases, two.

In addition to the above sources of uncertainty, interpretation of pressure-pulse tests are subject to the uncertainties associated with flow field geometry (radius of influence) and fluid properties described for injection tests. These uncertainties may introduce an error factor of about two to three in calculated permeability.

2.1.3 Transient Well Tests (Constant Discharge)

Transient well tests of the constant discharge type represent a large suite of borehole tests that have been developed in the petroleum and groundwater fields. In their simplest form, they are used to evaluate the transmissivity and storage of an aquifer or fracture zone surrounding a borehole pumped at constant discharge. In more complex forms (Earlougher, 1977), the method can theoretically be used to evaluate leakage, double porosity behavior, boundary effects, anisotropy, heterogeneity, single fracture flow behavior, wellbore storage and borehole skin effects, etc. from single and multiple borehole pressure responses. The method of analysis of the observed pressure transient response is usually to fit the data to type curves characteristic of the assumed or known conditions. The major pitfall associated with transient well test methods is that the interpretation of formation characteristics and hydraulic properties is non-unique (Ershaghi and Woodbury, 1985). Combinations of different formation properties and flow regimes can yield identical pressure transient response. To overcome this difficulty, which can translate into

uncertainty in permeability estimation of several orders of magnitude, it is necessary to utilize other hydrogeologic and geologic data from borehole and surface studies to verify that the flow regime selected is most appropriate for the test at hand.

Assuming that the flow regime is well known, the observed pressure response in a borehole is a function of borehole boundary conditions (wellbore storage and skin), far-field boundary conditions and formation hydraulic properties of permeability and specific storage. It is generally recognized that in fractured rocks, the influence of borehole and far-field boundary conditions are important as a consequence of low borehole flow rates and finite fracture extent, respectively. Testing and analytical methods need to consider the influence of these parameters in determining formation hydraulic properties.

2.2 SPECIFIC STORAGE

The specific storage of a porous medium is a measure of the medium's ability to supply, or add to, water from/in storage in response to changes in head. Specific storage is of interest only in systems subject to transient perturbations since in a steady-state system the change in stored water is zero.

The specific storage of a porous medium may be calculated using two approaches. One technique involves determining the specific storage based on the results of transient hydraulic tests (i.e., as the result of parameter fitting to observed data). Typical of this approach are the type curve analyses proposed by Cooper et al. (1967) and Bredehoeft and Papadopulos (1980). Such an approach can be used to obtain a reliable estimation of the formation's transmissivity (i.e., hydraulic conductivity x formation thickness) and, in principle, should be capable of providing an estimate of the storage coefficient. However, as pointed out by Cooper et al. (1967), Papadopulos and

Cooper (1967), Bredehoeft and Papadopulos (1980) and Black (1985), the matching of observed data to the type curves depends on the shape of the type curves which unfortunately change very little for several orders of magnitude change in storage coefficient. For this reason, the determination of specific storage by this method has questionable reliability. Barker and Black (1983) also examined the suitability of a conventional porous medium analysis for slug tests conducted in fractured rock. They found that the porous medium model could be used to obtain a reasonable estimate of the transmissivity (e.g., within a factor of two to three) but that storage coefficients could be in error by as much as a factor of 10^6. In summary, although it is theoretically possible to obtain storage coefficient estimates from hydraulic tests, in practice, these estimates have been found to be unreliable.

Another method of estimating the storage coefficient is to evaluate its individual components. As discussed in detail in an earlier report (GTC, 1986), the specific storage (S_s) of a medium can be defined as:

$$S_s = \rho g \, (C_r + \theta C_w) \qquad (2.5)$$

where ρ = fluid density (ML^{-3});
θ = total porosity (dimensionless);
C_r = formation compressibility (T^2LM^{-1});
C_w = fluid compressibility (T^2LM^{-1});
g = gravitational acceleration (LT^{-2}).

Most of the parameters comprising the storage term can be determined with a reasonable degree of accuracy. The fluid density can be determined by a variety of techniques, the most accurate is probably by sampling and measurement in the laboratory. In general, fluid density variations are small compared to variations in other parameters. Fluid compressibility can also be determined by laboratory measurement, although for most applications this value can be assumed

constant (Pearson, 1980). The total porosity of the formation (including matrix and fracture porosities) can be estimated reasonably well from laboratory techniques on cores. The matrix porosity measured from intact cores is typically much larger than the fracture porosity and comprises the majority of the total porosity. The compressibility of the formation is one of the terms possessing the highest uncertainty in the specific storage calculation. In fractured dual porosity rock, the total formation compressibility includes fracture compressibility and matrix compressibility.

Little work has been performed in characterizing in situ formation compressibility for the purpose of hydraulic test analysis. The majority of information describing the elastic properties of crystalline rocks has been collected for the purpose of performing rock mechanics analyses. Most of this information has been the result of compression tests (triaxial and uniaxial) performed on cores with a smaller amount of information resulting from borehole deformation techniques, such as dilatometers and borehole jacks (e.g., Carlsson and Olsson, 1982). It is questionable as to the appropriateness of such measurements for inclusion into specific storage estimates. One of the factors contributing to this uncertainty is the scale of the measurements obtained by these techniques. Most laboratory and borehole test methods use a relatively small sample size. The extrapolation of such measurements to a much larger scale is unproven.

A number of researchers (e.g., Gale, 1977) have also attempted to examine the in situ deformation that occurs in discrete fractures during hydraulic tests. It is not currently possible to relate such information to formation compressibility.

The range of compressibility values for intact (unfractured) rock obtained by borehole and laboratory tests is relatively narrow with the majority of values falling within $\pm$ 50% of the mean value (Tammemagi and Chieslar, 1985). For this reason, and due to the uncertainty associated with the use of this information in storage

coefficient determinations for hydraulic programs, only limited effort was expended in compiling elastic rock properties available from rock mechanics programs. The majority of the effort in the compilation of storage related parameters has therefore been directed at the compilation of porosity estimates.

2.3 FRACTURE CHARACTERISTICS

The primary fracture information recorded in crystalline rock environments includes:

- orientation;
- spacing/density;
- length;
- aperture;
- fracture surface roughness;
- infilling properties.

A variety of different methods are used to measure each of these parameters depending upon the location of the rock mass being characterized (i.e., surface versus subsurface). For example, surface mapping may be used both for outcrops and the faces of shafts and drifts of mines, tunnels and other underground facilities. Fracture information predominately obtained includes: strike, dip, trace length, and location (relative to a reference line) although other information such as aperture, roughness, trace length censoring (i.e., fracture length exceeds map area) and truncation level (fracture less than a certain length are not mapped) (Rouleau and Gale, 1985) and the nature of infilling material may be recorded. It is important to know the size of the area being mapped, since small areas may not be representative of the overall fracture system and may bias the trace length sample through censoring.

Core logging is another method of obtaining fracture information and in many aspects is very similar to surface mapping techniques. While fracture densities may be obtained from non-oriented core, the majority of useful information is obtained from oriented cores. Oriented cores, together with borehole direction surveys, may be used to obtain strike and dip information of the fractures contained within the cores. It is important to realize that many boreholes are not drilled straight and it is the borehole direction at the point of fracture intersection (as opposed to an average over the borehole length) that should be used. While core logging is incapable of providing trace length information, the estimates of dip angle are probably more reliable than those obtained from surface mapping. Core logging, as with all borehole characterization methods, exhibits a bias towards the sampling of features oriented perpendicular to the borehole. That is, fractures that approximately parallel the borehole orientation will either be under-sampled or missed altogether. Aperture measurements obtained from cores should generally be regarded as unrepresentative of in situ conditions since the core is no longer subject to the natural stress field and may also become separated during coring and retrieval activities.

The primary borehole geophysical logs that are used to obtain fracture information include borehole television and acoustic televiewer, while other useful logs include caliper and tube wave. Borehole television can be used to obtain estimates of fracture location, orientation (strike, dip), spacing and aperture. The collected data should be corrected for non-vertical and non-uniform plunge as well as variation in borehole diameters. The acoustic televiewer can be used to obtain information on fracture location, orientation, spacing and aperture. As with the borehole television log, corrections are required for non-vertical boreholes and changes in borehole diameter. Caliper logs can be used to obtain estimates of

fracture aperture although crumbling of the fracture at the borehole wall may lead to overestimates of the fracture aperture. Tube wave logs may be used to obtain information regarding fracture location and relative fracture aperture.

The errors associated with the various fracture characterizations depend upon the end use of the collected data. If for example, the purpose of the data is to provide a qualitative description of the integrity of the rock mass, then many errors may not be significant. If, however, the data are to be used for quantitative purposes (e.g., incorporation into a stochastic model), the resulting errors are likely to be of greater significance.

3. EVALUATION OF SITE SPECIFIC DATA

3.1 STRIPA MINE

3.1.1 Permeability

Permeability data for the Stripa site have been reported primarily by Olkiewicz et al. (1978), Lundstrom and Stille (1978), Forster and Gale (1980, 1981a, 1981b), Thorpe et al. (1980), Gale (1981) and Wilson et al. (1983).

The most complete and well described permeability data for the Stripa mine are those of Gale (1981). Subsequent papers (Gale et al., 1982a, 1982b, 1983; Gale and Rouleau, 1983) presented the same data with interpretations. The data of Gale (1981) are generally of high quality, primarily as a result of detailed descriptions of experimental procedures, test equipment, data handling and processing procedures and analytical methods. The data reporting provided by Gale (1981) is for the most part a good example for subsequent test programs to try to achieve. The detailed descriptions of test procedures and equipment and analytical methods, readily facilitate evaluations of the suitability of the test procedures to collect the basic data, the validity of the analytical methods and assumptions to determine permeability and the overall quality and representativeness of the permeability data.

Gale (1981) reported permeability data determined from straddle-packer injection and withdrawal testing in boreholes drilled from surface and from underground. The test procedures described by Gale (1981) are thorough but show some shortcomings which translate into uncertainty in calculated hydraulic conductivity and permeability.

The test procedures indicate the range of reliable flow rate measurement (Table 3.1) and pressure measurement as well as criteria to determine when steady conditions were achieved. Steady flow and pressure conditions were assumed when three consecutive flow and pressure readings (over several minutes span) showed changes less than 5% and less than 0.0003 MPa, respectively. These criteria are rigorous and in themselves are not expected to introduce any significant uncertainty in calculated hydraulic conductivities.

In the surface borehole injection tests described by Gale (1981), considerable uncertainty in formation pressures at depth existed as a result of the low fluid pressures (due to mine drainage) and the lack of a downhole valve to isolate the test interval from the surface flow tanks and the borehole injection tubing. To reduce this uncertainty, the flow rate per unit injection head data was determined from two injections rather than one above the formation pressure. This introduces some uncertainty in calculated permeabilities as a result of possible non-linearities in the injection pressure - flow rate relation. This error is thought to be less than the error factor of two to three introduced by uncertain flow geometry and neglecting storage in the medium.

The low flow measurement capability was described by Gale (1981) as 0.01 $mL \cdot min^{-1}$. For these low flow rates, fluid temperature measurement is essential for reliable data. Although Gale (1981) reported measurement of flow tank temperature using a thermocouple and borehole probe temperature using a thermistor, it is not clear how or whether this temperature data were considered in assessing the reliability of the low flow rate measurements. An additional drawback of the downhole temperature sensor was its location. Ideally the temperature sensor should be located in the centre of the test interval where it would be in contact with the greatest volume of test fluid. The downhole thermistor described by Gale (1981) was placed within an instrument pod located above the upper packer. In this location, the recorded temperature is likely

Table 3.1. Flow Rate Measuring Ranges for Borehole Hydraulic Test Program at Stripa (from Gale, 1981)

---

1. Injection Line - Air bubble method

Lower limit:
- Position of air bubble can be determined to within ± 1.5 mm;
- Thus to obtain 1% accuracy the bubble must move 150 mm, giving for a 30 minute test a minimum flow rate of 0.056 mL/min;
- For 120 minute test minimum flow rate is 0.014 mL/min;

Upper limit:
- Timing error ± 0.2 seconds;
- Thus to obtain 1% accuracy a minimum of 20 seconds of injection time is required;
- For a one metre long bubble tube this provides a maximum flow rate of 34 mL/min. A five metre bubble tube would provide a maximum flow rate of 150 mL/min (maximum practical limits).

2. Small Flow Tank - Used primarily on SBH-2

Lower limit:
- Transducer accuracy is 0.002 VDC (volts DC);
- 1% accuracy requires a change of .2 VDC;
- A change of 1.0 VDC in transducer reading is equal to 6.25 mL of water;
- Thus minimum volume for 1% accuracy is 1.25 mL;
- Minimum flow rate for a 30 minute test is 0.042 mL/min;
- Minimum flow rate for a 120 minute test is 0.010 mL/min.

3. Larger Flow Tank - Used primarily in testing SBH-1

Lower limit:
- Transducer accuracy is 0.002 VDC;
- 1% accuracy requires a change of .2 VDC;
- A change of .00000206 VDC is equal to 1 mL of water;

Table 3.1. Flow Rate Measuring Ranges for Borehole Hydraulic Test Program at Stripa (cont'd)

- Thus a minimum volume for 1% accuracy is 9708 mL of water;
- For a 30 minute test the minimum flow rate is 323 mL/min;
- For a 120 minute test the minimum flow rate is 80 mL/min.

* Acceptance of a 10% accuracy would permit one to measure flow rates on the order of 10^{-3} mL/min.

** Upper limits on the flow tanks is determined by the volume of water in each tank and the length of time required to obtain good test results.

*** Several different sizes of tanks were used in testing SBH-2 and one intermediate size tank was used in testing the other boreholes. These tanks provide flow rates that complimented the ranges provided by the tanks described above.

influenced by heating of the electric pressure transducer as well as the borehole fluids above the test interval.

Gale (1981) used the Hvorslev (1951) shape constant to determine hydraulic conductivity from measured flow rates and pressures. Gale uniformly used r_b equal to 10 m which for lower hydraulic conductivity intervals (i.e., less than 10^{-6} $m \cdot s^{-1}$) may introduce up to a 50% overestimation of hydraulic conductivity.

In calculating permeabilities from hydraulic conductivities, Gale (1981) assumed fluid viscosity and density properties of ordinary water at 12°C. The error associated with this assumption is unlikely to exceed a factor of two for the described field conditions of Stripa.

In summary, the permeability values described by Gale (1981) are thought to be reliable to within a factor of two to three for permeabilities above 10^{-18} m^2 (hydraulic conductivity of 10^{-11} $m \cdot s^{-1}$). This level of reliability is considered good in light of the fact that the permeability of fractured plutonic rock is expected to vary between 10^{-22} and 10^{-13} m^2, over nine orders of magnitude.

The lower measurement limit of permeability by injection testing of 10^{-18} m^2 (10^{-11} $m \cdot s^{-1}$ hydraulic conductivity) was determined primarily by flow rate measurement capabilities. This permeability limit appears appropriate and introduces some bias in the permeability versus fracture frequency data (Figure 3.1) and the permeability versus depth data (Figure 3.2) reported by Gale et al. (1982a). Permeabilities below 10^{-14} cm^2 shown in Figures 3.1 and 3.2 are of limited reliability and may more likely represent maximum values. The result of this uncertainty

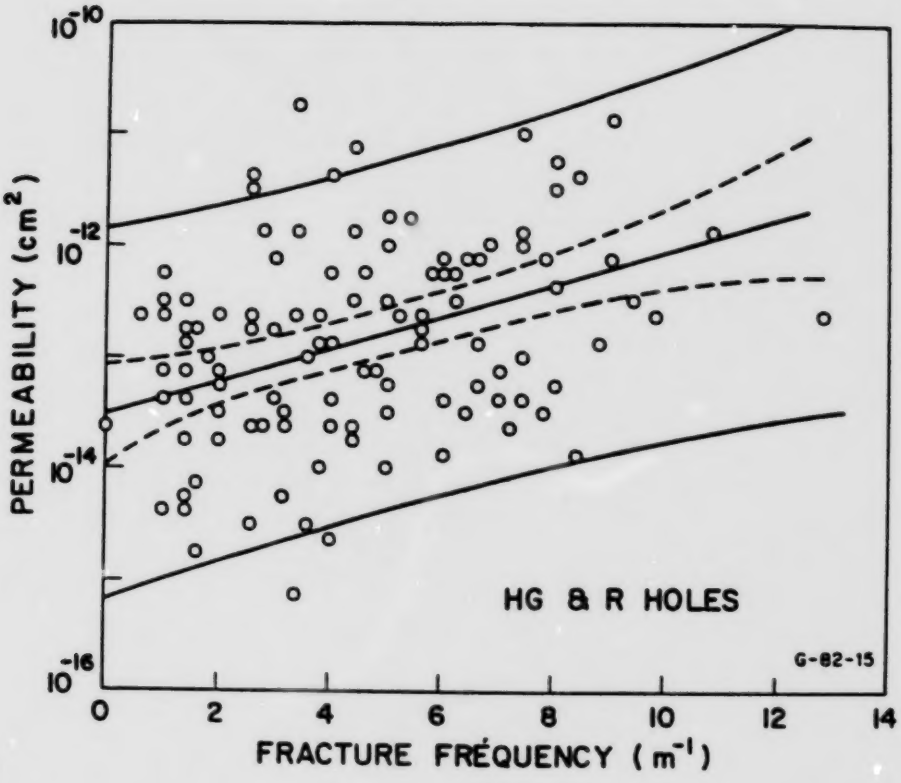


Figure 3.1 Permeability versus fracture frequency for all HG and R boreholes (after Gale et al., 1982a)

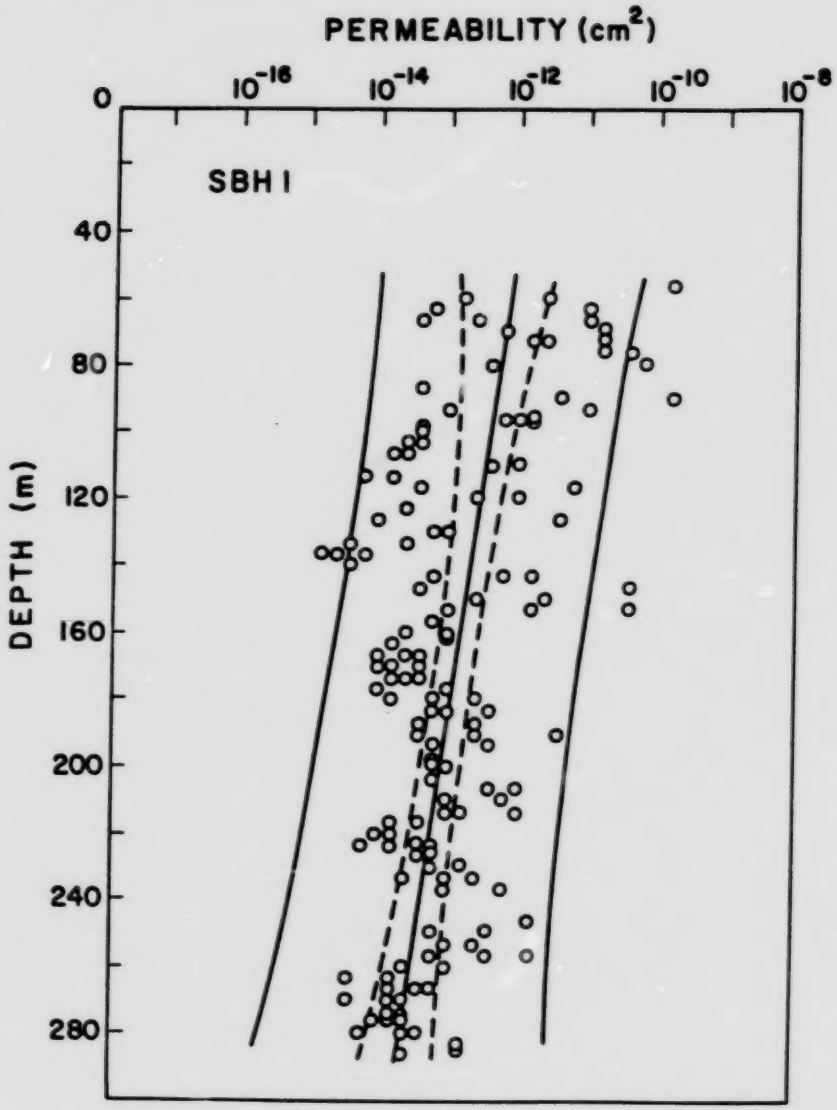


Figure 3.2 Permeability versus depth from injection tests in SBH-1 (after Gale et al., 1982a)

in the low permeability data is that the general trends shown in Figures 3.1 and 3.2 may be more pronounced than indicated. Thus, a stronger correlation may exist between permeability and depth and permeability and fracture frequency than is shown by the data of Gale et al. (1982a). On Figures 3.1 and 3.2, the central full line is the least-squares regression line; on each side of this line, the 95% confidence limits are shown for individual predicted values (full lines) and for mean predicted values (dashed lines).

An equally comprehensive reporting of test procedures, test equipment and analytical methods for field hydraulic testing at Stripa, was given by Forster and Gale (1981b). Forster and Gale (1981b) utilized pressure-pulse transient testing to measure the permeability characteristics of the rock surrounding the ventilation drift at 340 m below ground surface. A summary paper of this field testing program is given by Forster and Gale (1980). The work by Forster and Gale (1981b) is of interest because it represents one of the first field applications and assessments of the use of pressure-pulse transient test techniques to measure rock mass permeabilities. The pressure-pulse transient technique was originally proposed by Brace et al. (1968) and in field application is capable of measuring permeabilities in the range of 10^{-21} m^2 to 10^{-14} m^2 (10^{-14} to 10^{-7} $m \cdot s^{-1}$ hydraulic conductivity). The pulse test data collected by Forster and Gale (as decay curves) were not analyzed to determine permeability but were compared to steady-state injection test data. Assuming that the injection test data were a reliable estimate of the permeability of the tested intervals, Forster and Gale reported that there was not consistent correlation between the permeability and the pressure-pulse decay characteristics. The lack of correlation between the two test results was thought by Forster and Gale (1981b) to be a result of three factors:

1) the complex nature of the fracture system;
2) the effect of compliant test equipment and
3) differences in radius of test influence.

The lack of correlation between pressure-pulse decay characteristics and steady-state permeabilities reported by Forster and Gale (1981b) may relate to test equipment difficulties. The variable (see Figure 3.3) and generally high test interval compressibilities reported by Forster and Gale, suggest leakage of air from packers into the test intervals and packer compliance or creep effects during the pressure-pulse tests. In fact, the lack of correlation observed by Forster and Gale is in part attributable to the variable compressibilities measured during the pressure-pulse tests. For equally conductive test intervals, a higher test interval volume - compressibility product will result in a delayed pressure decay curves.

Forster and Gale (1981b) and Gale and Raven (1979) experimentally demonstrated that higher compressibility test intervals (resulting presumably from compliant packers) result in delayed decay curves and a underestimation of permeability by a factor of two.

In summary, the pressure decay curves presented by Forster and Gale (1981b) are thought to be reliable and, using existing analytical techniques (Bredehoeft and Papadopulos, 1980) and measured volume-compressibility products, most of the curves could be expected to yield permeability values that would be accurate to within a factor of two to three. In fractured plutonic rocks, this level of reliability is considered adequate. However, for test durations of hours and more, it would be important to use the temperature data that were reportedly collected for selected intervals in order to reliably determine rock mass permeability from the pressure decay curves.

Additional field hydraulic tests for a 400 m long borehole drilled in the Stripa mine were reported by Olkiewicz et al. (1978). Olkiewicz et al. reported permeability values (as hydraulic conductivity in $m \cdot s^{-1}$) determined from steady-state fluid withdrawal tests using straddle packers. The test equipment and method

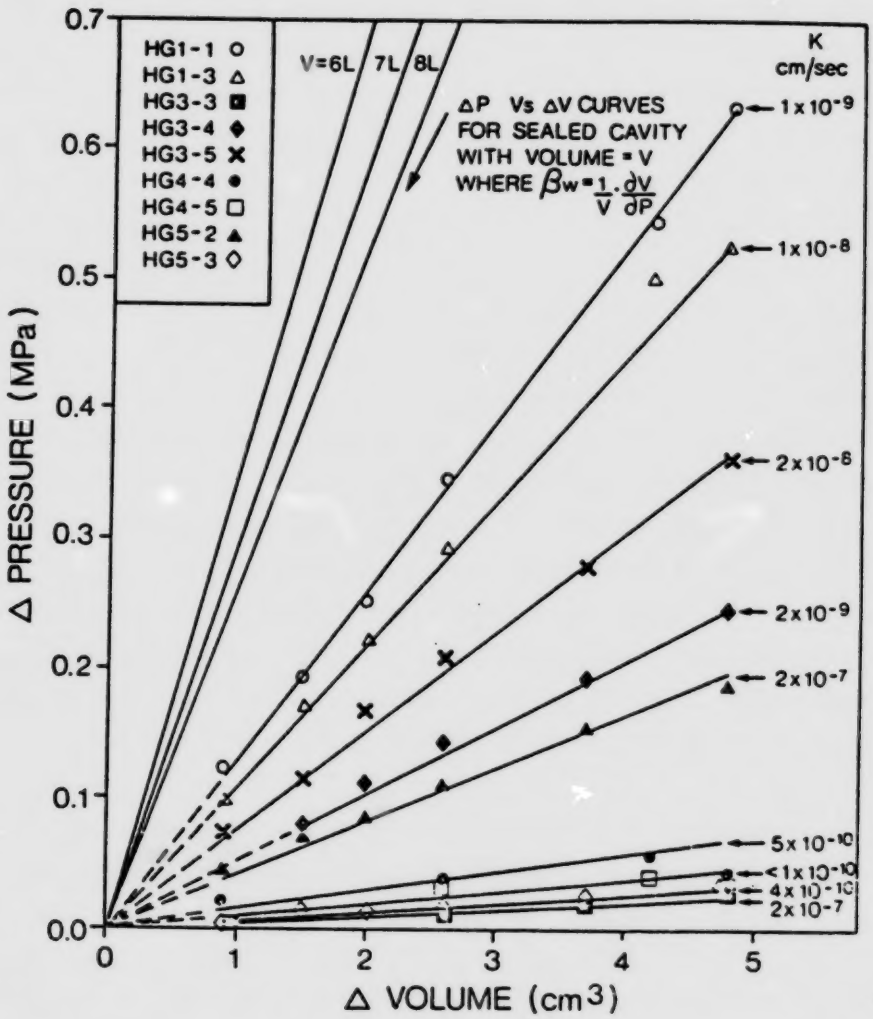


Figure 3.3 Pulse pressure (ΔP) resulting from imposed displacement volume (ΔV) (after Forster and Gale, 1981b)

used to perform these tests are only briefly described by Olkiewicz et al. Fluid withdrawal pressures were measured using a submersible pressure transducer and flow rates were measured using a graduated cylinder and stopwatch. The lowest measurable flow rate was reported as 0.6 $mL \cdot min^{-1}$ which is large enough to make thermal expansion effects negligible. The minimum measurable flow rate however was determined from consideration of gas flow observed in the borehole and the test tubing. Olkiewicz et al. used the shape factor of Moye (1967) and equation (2.1) to determine hydraulic conductivity from measured flow rates and pressures/heads.

Because many of the test intervals reported by Olkiewicz et al. had low permeability, many of the flow rate measurements and equilibrium fluid pressure measurements have uncertainty. Withdrawal pressures used to determine hydraulic conductivities were only reliably measured in the relatively few high permeability sections of the deep borehole. Formation pressures were assumed to vary linearily with depth in the borehole and were interpolated between high-permeability test intervals. The interpolation may introduce an error of up to a factor of two in calculated hydraulic conductivity. In addition to this error, fluid flow around packers was recognized as a possible although unquantified source of error in flow rate measurement and therefore calculated hydraulic conductivity.

The hydraulic conductivity versus depth plot of Olkiewicz et al. (Figure 3.4) has an apparent decreasing permeability versus depth trend to 300 m depth that is principally an artifact of the testing methodology. With increasing depth, the withdrawal fluid pressures increased as a consequence of the increase in the formation fluid pressure away from the mined opening. With a constant minimum flow rate of 0.6 $mL \cdot min^{-1}$, this increase in withdrawal fluid pressure results in a decrease in the minimum detectable hydraulic conductivity. In summary the hydraulic conductivity numbers reported by Olkiewicz et al. are thought to be reliable to within a

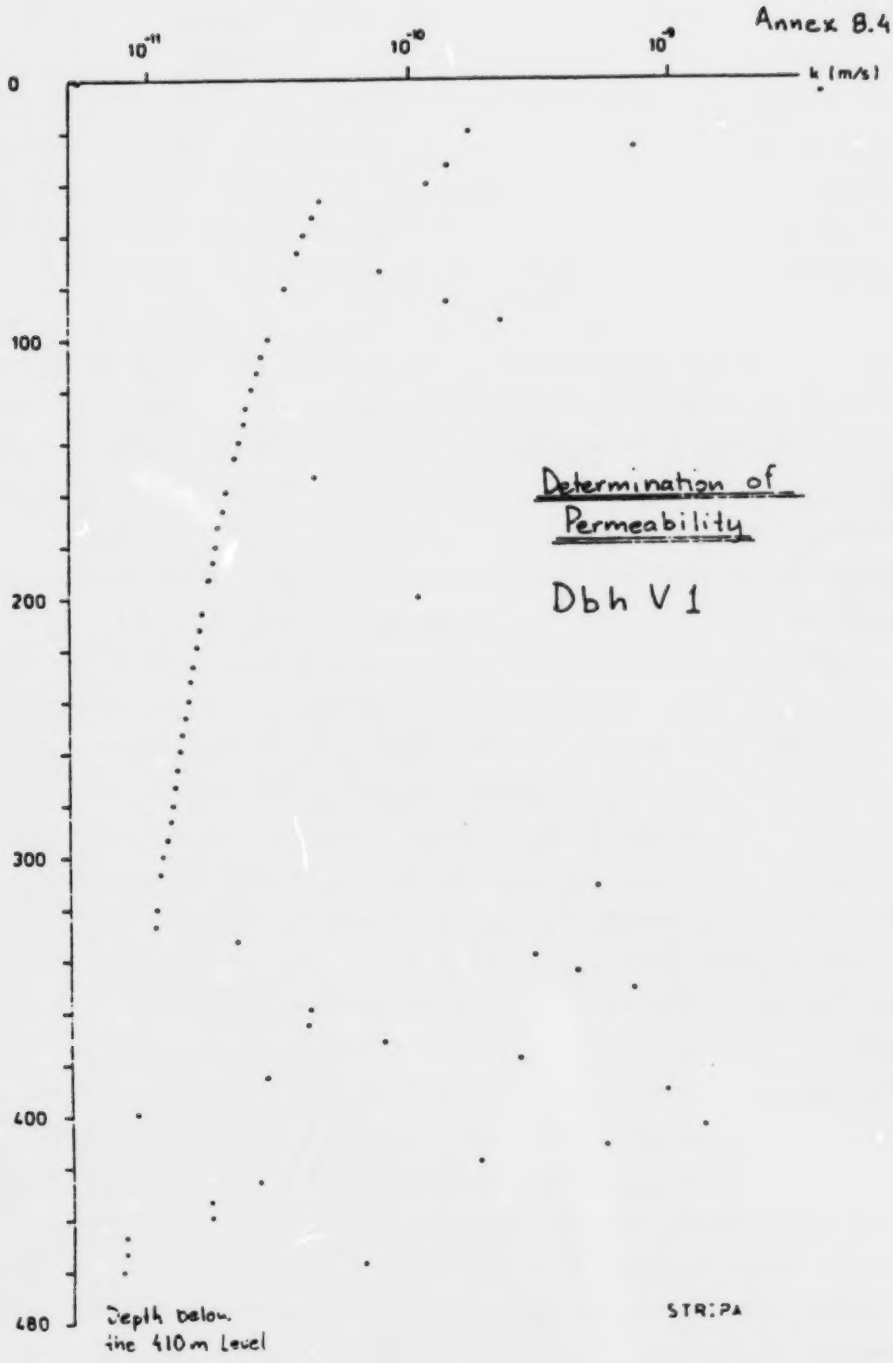


Figure 3.4 Hydraulic conductivity versus depth for borehole DBh V1 (after Olkiewiez et al., 1978)

factor of three for test results above 10^{-10} $m \cdot s^{-1}$. Below 10^{-10} $m \cdot s^{-1}$ the results are less reliable as a consequence of borehole pressure history effects and unreliable flow rate measurement. It is also likely that several of the high hydraulic conductivity tests (i.e., below 320 m) performed in highly fractured sections of the borehole may have been subject to packer bypass (leakage) and hence overestimation of hydraulic conductivity.

Lundstrom and Stille (1978) described the methods and results of multiple borehole permeability tests in the floor of the 360 m level in the Stripa Mine. Hydraulic tests were performed in two places between 16 vertical boreholes drilled at 1.5 m radial distance from a central vertical borehole. Single and straddle packer tests were performed in each of the 16 peripheral boreholes and a large scale permeability test was performed by injecting fluid at a constant pressure in the peripheral boreholes and measuring steady-state flow rate and pressure in the central borehole. This test was in essence an injection test with a controlled far-field pressure boundary. Lundstrom and Stille reported that the single packer tests in the peripheral boreholes yielded lower hydraulic conductivies (by up to a factor of 7) than the straddle-packer tests conducted in the same boreholes. Lundstrom and Stille suggested that this difference was a result of spherical flow field losses at the ends of the test interval; the losses being greater with straddle packers than with a single packer. This explanation is inconsistent with the described experimental method as spherical flow losses, if they occur, must act at both the single packer and the bottom of the borehole. Also, as flow occurs through an uncertain network of fractures, it is not clear that flow losses due to spherical flow field geometry (end effects) should have occurred during these experiments. An alternate and equally plausible explanation for the observed difference in test results is that of leakage of injected fluid around the packer seal. Details of the test equipment (type of packers, inflation pressures, etc.) were not provided by Lunstrom and Stille and therefore this explanation can not be excluded.

Lundstrom and Stille also reported that the results of the injection tests in the peripheral boreholes yielded hydraulic conductivities that were 10 to 20 times higher than the large scale multiple borehole interference tests. This overestimation of hydraulic conductivity is to be expected as each of the single borehole tests were performed with the other peripheral boreholes open. These additional open boreholes provide a complex far-field boundary condition which is difficult to consider in subsequent analysis of test data, although Lundstrom and Stille attempted to consider these effects using a porous media analysis. More reliable single well tests would require sealing of each of the other peripheral boreholes with packer assemblies.

The results of this large scale permeability test yielded hydraulic conductivities for the rock mass of between 4×10^{-11} $m \cdot s^{-1}$ (at 10°C) and 2×10^{-11} $m \cdot s^{-1}$ (at 36°C). These results appear reasonable and as Lundstrom and Stille recognized they are more reliable than the single borehole tests as a consequence of 1) more controlled experimental conditions, 2) less chance of fluid leakage from test equipment, and 3) better defined boundary conditions.

A truly large scale permeability test for the Stripa mine was reported by Wilson et al. (1983). In this experiment, groundwater flow to a 33 m long, 5 m diameter drift was measured as the net moisture collected by a ventilation system. With fluid pressures measured in 90 packer-isolated intervals in the rock mass, a hydraulic conductivity was calculated from the measured flow rates and calculated hydraulic gradients. Assuming radial flow in a homogeneous porous medium, Wilson et al. reported hydraulic conductivities for the rock mass of about 1×10^{-10} $m \cdot s^{-1}$ and the existence of a lower hydraulic conductivity skin equivalent to about 40 m head in the first few metres

of the drift walls. The experiment was repeated at several air temperatures, and in conjunction with the controlled and well described experimental conditions (Galbraith et al., 1981), the results are considered a reliable estimate of the bulk hydraulic conductivity of a rock mass on a large scale (200,000 m^3 volume).

Laboratory measurements of permeability of samples of fractured Stripa granite were reported by Forster and Gale (1980) and Thorpe et al. (1980). Forster and Gale (1980) performed pressure-pulse transient tests and steady-state injection tests on a 5.4 mm diameter, 102 mm long sample of a natural fracture subject to confining pressures of 3.4 to 13.8 MPa. The purpose of the tests conducted by Forster and Gale was to evaluate the effect of packer compliance and the usefulness of pressure-pulse transient tests in permeability measurement. The porous media hydraulic conductivity values reported by Forster and Gale ranged from 1×10^{-9} to 9×10^{-8} $m \cdot s^{-1}$. The hydraulic conductivity values were determined by the straight line graphical method of Brace et al. (1968). The method is appropriate for these tests as the storage capacity of the fracture is negligible compared to the storage capacity of the upstream and downstream reservoirs. The consistent straight lines obtained by Forster and Gale (see Figure 3.5) confirm the appropriateness of the analytical technique. The calculated hydraulic conductivities, however, were determined from knowledge of the volume- compressibility product of the test equipment. Forster and Gale assumed that the compressibility of the test equipment was due solely to the compressibility of water which, as shown in Figure 3.5 for different borehole seals, may not have been the case. The likely higher compressibilities of the test equipment will result in slower decay curves. Because the data were analyzed using the lower compressibility values attributable solely to water, the calculated hydraulic conductivities are underestimated possibly by a factor of two. The steady-state hydraulic conductivity values confirm this result. However, while the steady-state hydraulic conductivity values

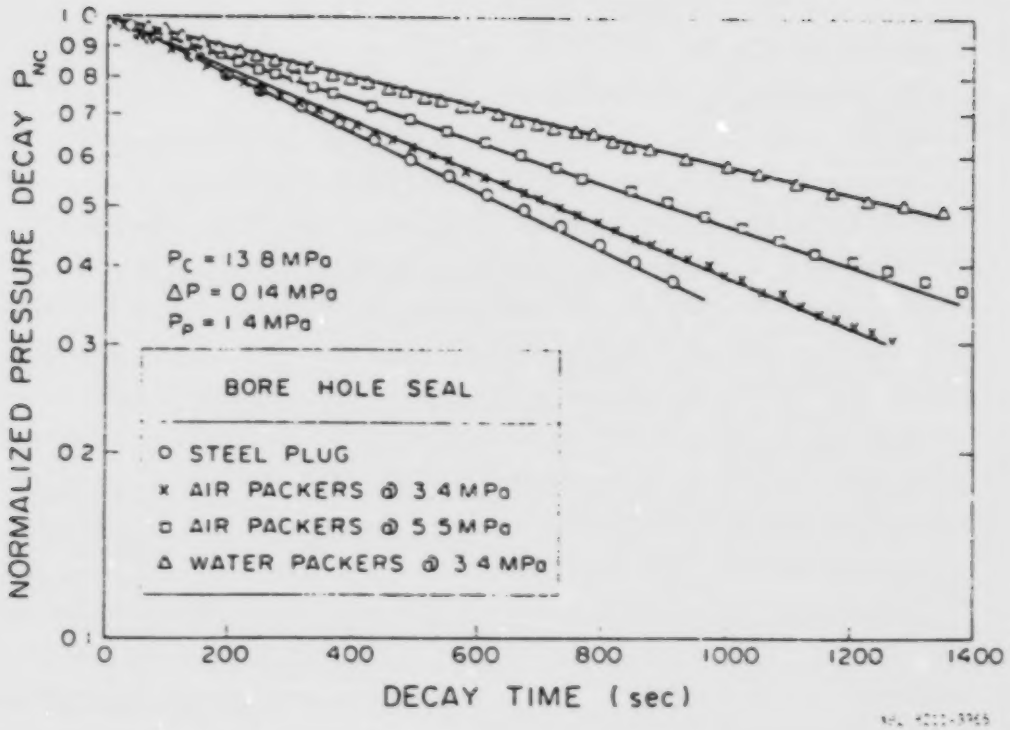


Figure 3.5 Log-normalized pressure decay versus decay time for a fractured sample of Stripa granite (after Forster and Gale, 1980)

for the core are likely accurate for the described experimental conditions, it is unlikely that the values from such a small sample are representative of in situ conditions at a much larger scale. Because of finite fracture extent and other scale considerations, the data of Forster and Gale likely overestimate the bulk permeability of the rock mass.

A larger sample of fractured Stripa granite measuring 1 m diameter by 2 m length was tested in the laboratory by Thorpe et al. (1980). Thorpe et al. initially used falling head tests and a set of straddle packers to test the hydraulic conductivity properties of the unloaded core which was highly fractured. Subsequent testing used injection tests during triaxial loading of the core. Several sources of uncertainty in calculating hydraulic conductivity from the falling heads were identified by Thorpe et al. The major sources of uncertainty related to the need to empirically correct the observed heads for frictional losses in the flow tubing, the influence of the unsaturated conditions of the core and non-laminar flow at high initial flow rates. The net effect of these uncertainties is that the hydraulic conductivities may only be accurate to within an order of magnitude. During the injection tests, the core was saturated and the major uncertainty relates to the likelihood of turbulent flow at the entrance to the fracture from the central injection borehole. The measured flow rates ($1 - 4\ L \cdot min^{-1}$) translated to Reynolds Numbers of 8,000 - 32,000 (reported by Thorpe et al., 1980) which is well beyond the suggested laminar flow limit for natural fractures at 10 - 100 (Louis, 1969). The hydraulic conductivities for the rock mass calculated from the injection tests ranged from $5 \times 10^{-5}\ m \cdot s^{-1}$ to $4 \times 10^{-6}\ m \cdot s^{-1}$, which given the likely turbulent flow conditions, may be underestimated by factors of two to three.

In addition to uncertainty in calculated hydraulic conductivities, there exists considerable uncertainty as to the representativeness of the sample of the bulk rock mass as a whole. The abnormally high permeabilities measured during testing likely result from disturbance of the highly fractured sample during drilling for sampling, overseas shipment and sample preparation for testing.

Comparison of permeability of the rock mass at Stripa determined by different methods and by different experiments provides a convenient assessment of the degree of representativeness of the data. By far, most of the field data were collected on the 335 - 360 m level(s). Data reported by Gale et al. (1982a) for boreholes around the ventilation drift tested by Wilson et al. (1983) show a geometric mean permeability of 9×10^{-17} m^2. This compares favourably with the permeability determined from the ventilation drift experiment at 1×10^{-17} m^2 and the multiple borehole test of Lundstrom and Stille at 5×10^{-18} m^2. The higher permeability numbers of Gale et al. (1982a) may result from an unreasonably high radius of test influence. Considering that the individual test results are assumed accurate to within a factor of two or three, the consistency of the test results are remarkable and suggest the rock mass at the 335 - 360 m level at Stripa has been reliably measured at 5×10^{-18} to 5×10^{-17} m^2. The use of different methods (single well injection tests, multiple borehole interference tests and ventilation experiments) confirms the reliability of these test methods for permeability measurement.

With reliable field results, it is possible to judge the representativeness of the laboratory data. The data of Forster and Gale (1980) (1×10^{-16} to 9×10^{-15} m^2) and Thorpe et al. (1980) (4×10^{-13} to 5×10^{-12} m^2) are clearly several orders of magnitude too high to be representative of in situ conditions and are influenced by sampling and scale effects.

3.1.2 Porosity

Only a limited number of values are available to describe the porosity of the granite at Stripa. Gale et al. (1982a, 1983) suggested an approach based on fracture charcteristics and effective apertures. Briefly, their method involves the construction of a number (one for each fracture set) of frequency distributions for fracture lengths and spacings. Two additional frequency distributions are also required, one of effective apertures as determined from borehole tests and the other of effective aperture as calculated from laboratory tests on single fractures. Porosity estimates are obtained by random sampling of the three distributions (i.e., length, spacing and aperture). Total fracture porosity estimates are obtained from the laboratory derived data while effective porosity estimates result from the borehole derived data. Using this approach, Gale et al. (1982a, 1983) obtained a mean effective fracture porosity of 10^{-5} and a mean total fracture porosity of 10^{-4} for six of the fifteen boreholes in the ventilation drift.

This approach is subject to considerable uncertainty. For example, as Gale et al. (1982a,b) pointed out, the effective apertures were calculated using the assumption of fracture walls being smooth and parallel which is in error since it ignores the effect of roughness. In addition, it should be pointed out that their approach inherently assumed that no cross-correlation existed between the fracture characteristic variables themselves. The validity of this assumption should be examined. Another difficulty associated with this approach is the use of apertures, based on flow measurements, for solute transport calculations. The major difficulty associated with such an approach, as with the method proposed by Gale et al. (1982a, 1983), is that they are unsubstantiated by field data. In spite of these difficulties, it can be said that the numbers estimated by Gale et al. (1982a, 1983) are likely order of magnitude correct.

3.1.3 Fracture Characteristics

Olkiewicz et al. (1978, 1979) described the results of fracture mapping and some core mapping undertaken at Stripa. Fracture mapping was conducted both at the surface as well as in underground excavations including the ventilation drift and the upper (338 m) and lower (360 m) drifts. Olkiewicz et al. (1979) also reported on work being conducted by Lawrence Berkeley Laboratory (LBL) including the description of cores from two surface boreholes, mapping of veins and fractures in a 22 m section of the ventilation drift, description of cores from boreholes drilled in this drift, fracture mapping of the time scale experiment, extensometer and full scale drifts as well as the description of core from numerous heater experiment instrumentation boreholes.

Olkiewicz et al. (1978, 1979) reported that the surface mapping was conducted on a 4000 m^2 outcrop located some 200 m north of the ventilation shaft. Olkiewicz et al. (1978) indicated that 26 fissures were observed in the outcrop. Given the typical fracture densities that exist in most granite bodies together with some of the fracture densities reported for the subsurface fracture mapping, it is apparent that Olkiewicz et al. (1978) used the term fissure to denote some type of large scale feature. Unfortunately, no criteria were given for such a distinction and the reason for excluding the smaller scale features is unclear. Olkiewicz et al. (1978, 1979) also summarized fracture frequency and orientation data (i.e., strike and dip) for the ventilation tunnel (walls and roof) as well as the lower and upper drifts (as projections upon horizontal planes). The chemical composition of some of the infilling materials was also reported. Little information was provided on the geometry of the subsurface excavations (e.g., lengths, widths, diameters, etc.) and no information pertaining to trace lengths or apertures was reported. Olkiewicz et al. (1979) used the results of the surface and subsurface maps to conclude that a high degree of conformity exists between the various

fracture systems. While this may be the case, care should be used in relating characteristics of large scale surface features with subsurface fractures of a significantly smaller scale.

Olkiewicz et al. (1979) also described core logging and fracture mapping conducted by LBL at the Stripa Site. The procedure used to log the core and the results obtained were described in more detail by Gale (1981) and will be discussed later. Mapping procedures and findings were also reported by Thorpe (1979) for the time scale heater experiment drift and Rouleau et al. (1981) for the ventilation drift. The ventilation drift mapping resulted in the collection of some or all of the following fracture data:

- type of fracture;
- orientation;
- trace length;
- aperture and infilling;
- fracture roughness.

Olkiewicz et al. (1979) reported that all fractures greater than 1 m in length were mapped and that this represented a level of detail greater than that expended for the general mapping of the excavation but a lesser degree of detail than that given the time scale and full scale heater sites. Rouleau et al. (1981) indicated that the fracture data collected as part of the mapping (e.g., orientations, trace lengths, and spacings) would form the basis for a statistical analysis of the fracture system in order to determine the degree of interconnectivity. If the information collected as part of this fracture mapping program is to be used for such an application, it is important to make a correction to account for the censoring of trace length data that occurs at the tunnel wall boundaries. In addition, both large fractures occurring at relatively large spacings and fractures oriented parallel to the drift will typically be underestimated by the fracture populations derived based on such a small surface area.

Both Thorpe (1979) and Olkiewicz et al. (1979) described the work conducted for the purpose of characterizing the fracture system of the time scale heater test drift. This work consisted of preparing a fracture map of the floor of the drift as well as core logs for 17 vertical and 2 inclined boreholes. Fractures which were shallow (less than 30° dip) or had a small trace length (less than 0.3 m) were not included in the floor map. Thorpe (1979) attempted to correlate fractures from the floor with those present in cores obtained from the boreholes drilled in the floor. This correlation procedure was basically a trial and error process based on extrapolated fracture planes and the similarity of surface and subsurface orientations as well as the similarity of infilling materials. Thorpe (1979) reported moderate success at correlating surface features and the upper portions of the borehole cores and was able to identify four large scale continuous features. While it is recognized that the fracture characterization was carried out for the purpose of providing definition for thermal mechanical experiments, Thorpe (1979) could have used alternate or supplementary techniques (e.g., by using tracers) to confirm the existence of specific fracture planes within boreholes. Thorpe (1979) used the results from the core logging of the vertical boreholes to fit fracture spacing data to log-normal distributions. Thorpe (1979) gave no justification for his choice of distribution nor did he provide any quantitative information regarding the resulting parameter fit (i.e., measure of goodness of fit). In addition, the use of such information should be restricted to planes parallel to the drift (i.e., normal to borehole axis) since the distribution will be biased to this orientation. Thorpe (1979) also used the results of the floor mapping to construct similar distributions for the trace length data. Also, justification for the choice of distribution and some quantitative measure of the goodness of fit were not provided. Again, the same restriction regarding the use of this data (i.e., planes parallel to drift) should apply. It is also important to

recognize that correlations between the various fracture features may exist, although given the present data base no way of determining such correlations is possible.

Olkiewicz et al. (1979) described the fracture characterization efforts conducted in the full scale heater experiment drift. Essentially the same techniques used to characterize the time scale drift were employed. A detailed map of the floor was prepared for all fractures in excess of 0.2 m. Maps were also prepared for the walls of the drift for fractures in excess of 1.0 m length. Subsurface data consisted of core logging some 102 boreholes (of which only 36 were oriented). Using the same approach as used in the time scale drift, a model of the subsurface fracture system was constructed. Only limited analysis and synthesis of the collected data were reported. Olkiewicz et al. (1979) compared the data to that collected in the time scale drift and suggested the absence of several distinct joint sets was indicative of an unrepresentative sample arising from the smaller sample size. While this may indeed be the case, it would seem unlikely since the mapped length of the full scale drift is over half the length of the time scale drift.

Gale (1981) described in detail the procedures followed in performing oriented core logging on six watertable boreholes, three inclined surface boreholes and six subsurface boreholes. Information recorded by the core loggers included:

- natural versus induced fractures;
- open or closed fractures plus an estimate of aperture where possible;
- form (i.e., plane, curved, irregular) of fracture surface;
- evaluation of roughness or weathering of fracture surface
- identification and description of fracture fillings;
- description of rock;
- fracture strikes and dips.

The only potential problem affecting this data lies in the qualitative nature of such data. This, coupled with the fact that 10 to 15 individuals were involved in the core logging process, would tend to result in inconsistencies in the core logging data. Gale (1981) acknowledged this fact, but indicated that insufficient manpower resources prohibited the duplicate logging of cores.

Gale et al. (1983) summarized the various fracture characterization efforts conducted at Stripa. They acknowledged difficulties such as censoring and sampling biases (e.g., truncation and size bias) associated with the development of statistical distributions for trace length data. Gale et al. (1983) also discussed the findings of Rouleau and Gale (1982) which presented quantitative results of fitting fracture spacing data to three different distributions. Lognormal distributions were found to be better suited than either exponential or Weibull distributions. Gale et al. (1983) also indicated that they attempted to correlate fracture orientations of long inclined surface boreholes ($\approx$400 m) but found scatter in the data to be too significant. Plots based on only the lower sections of the boreholes showed significantly less scatter.

It is difficult to compare the sets of fracture data collected at Stripa since the majority of the data were collected either from different sets of boreholes, surface outrcrops or wall, floor and ceiling exposures in tunnels. It can be stated that certain researchers more fully document their approaches, findings and associated limitations (e.g., Gale et al., 1983; Rouleau and Gale, 1982) and as such a higher degree of confidence can usually be placed in their data.

3.2 SWEDISH SITES

3.2.1 Permeability

Permeability (hydraulic conductivity) data for other Swedish sites were principally reported in the context of site investigations for the Swedish radioactive waste disposal program. Hult et al. (1978), Landstrom et al. (1978), Carlsson et al. (1979, 1984a, 1984b), Almen et al. (1981) and Ahlbom et al. (1983a,b,c,d) described the results and interpretations of hydraulic tests performed at the Sterno, Finnsjon, Gidea, Kamlunge, Fjallveden, Svartboberget, Krakemala, Studsvik, Avro, and Karlshamn sites. The bulk of the permeability values reported by these investigators are from single and straddle-packer injection tests performed in open boreholes that were drilled from surface.

The test procedures and reporting of test results from early investigations at the Krakemala, Avro, Finnsjon, Karlshamn, Sterno and Studsvik sites are somewhat different from the so-called standard and revised test programs completed after 1979 at the Gidea, Kamlunge, Fjallveden, and Svartboberget sites.

The bulk of the pre-1979 test results were reported by Hult et al. (1978), Carlsson et al. (1979) and Almen et al. (1981). Most of these tests were straddle-packer tests completed using 2 to 3 m length test sections. The tests were performed using submersible pressure transducers to monitor test interval pressures and with flow rate measurement at surface. Injection pressures of 0.2 and 0.4 MPa were used. Flow rate measurement capability was 65 $L \cdot min^{-1}$ to a minimum of 0.85 $mL \cdot min^{-1}$. However as a result of straddle packer leakage, determined from comparison of single packer test results and straddle-packer tests (see Figure 3.6), the lowest reliabily measured hydraulic conductivity was thought to be about 2×10^{-9} $m \cdot s^{-1}$ for the average test conditions described above.

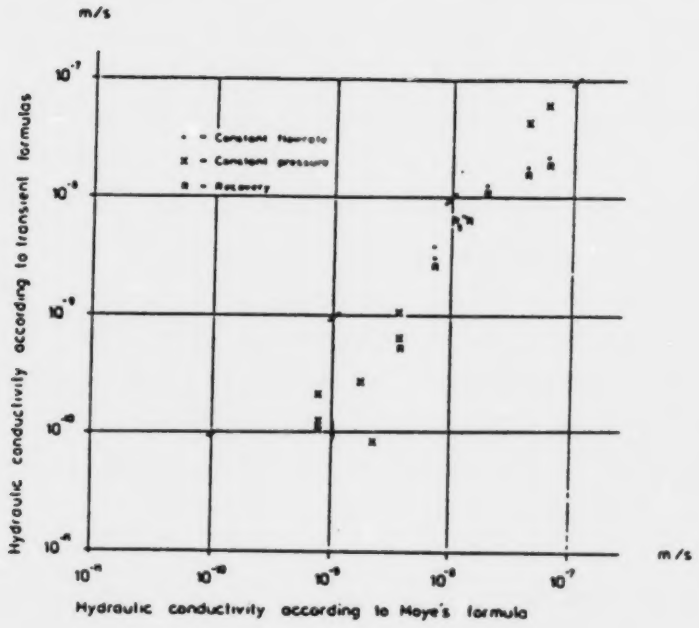


Figure 3.6 Comparison between values of hydraulic conductivity determined from the formula by Moye and from transient testing (after Carlsson et al., 1979)

Hydraulic conductivity was determined from the measured steady-state flow rates and pressures using equation (2.1) and Moyes shape factor. The use of Moyes shape factor to approximate the flow geometry and neglecting storage in the medium will likely result in an overestimation of permeability of the medium by a factor not likely to exceed three (Doe and Remer, 1981) but generally increasing with decreasing permeability. In some hydraulic tests reported by Carlsson et al. (1979), a transient analysis method (Jacob and Lohman, 1952) was used to estimate hydraulic conductivity in the pre-steady-state condition of the injection tests. Carlsson et al. (1979) (Figure 3.6) observed an overestimation of hydraulic conductivity using Moyes steady-state analysis method compared to results using the transient method that was greatest at lowest conductivity (by a factor of about three) and decreased with increasing conductivity. This field result appears to substantiate the theoretical work of Doe and Remer and may provide confirmation of the reliability of the steady-state hydraulic conductivities calculated using the injection tests. However, early transient flow rate response during constant pressure injection tests may be complicated by:

- packer creep as a result plastic deformation of the rubber element;
- borehole skin effects;
- pressure and temperature history effects as a result of open borehole conditions.

These effects, although largely unquantified, are expected to be greatest in lower permeability media. Given these uncertainties, it is believed that transient test methods are unlikely to yield more reliable estimates of permeability than can be obtained using the conventional steady-state assumptions.

The comparison of single packer and double packer test results described by Almen et al. (1981) and used to suggest double packer leakage is also subject to some uncertainty. The uncertainty relates to the representativeness of the flow rate and formation pressures obtained when testing long sections of open borehole with single packer assemblies. Because hydrogeologic systems are in a dynamic state, open boreholes will intersect a distribution of hydraulic head regimes and groundwater will flow along the borehole between zones of higher and lower hydraulic heads. By testing long sections of borehole with single packers, some fluid flow rate will exist between the high and low hydraulic head regimes in what is presumed to be a zero flow or equilibrium condition. Because the initial pressure conditions are not uniform as a result of open borehole flow, it is not clear that injection tests conducted over long test intervals of variable permeability with single packers should yield similar results to short interval double packer tests where inter-borehole flows are less likely. Also, if there is high permeability at depth, successive single packer injection tests require very accurate flow rate measurements to identify low permeability sections. These two considerations cast some doubt on the reliability of Figure 3.7, presented by Almen et al. although it is recognized that in low permeability formations (less than 10^{-10} $m \cdot s^{-1}$) packer leakage or bypass can be significant and limit the lower measurement capability.

In summary, the pre-1979 data for other Swedish sites is likely reliable to within a factor of two for hydraulic conductivity above 10^{-9} $m \cdot s^{-1}$.

After 1979, a more standarized testing procedure was adopted for investigations of Gidea, Kamlunge, Fjallveden and Svartboberget sites. Permeability (hydraulic conductivity) data are principally reported by Ahlbom et al. (1983a,b,c,d) and Carlsson et al. (1984a,b).

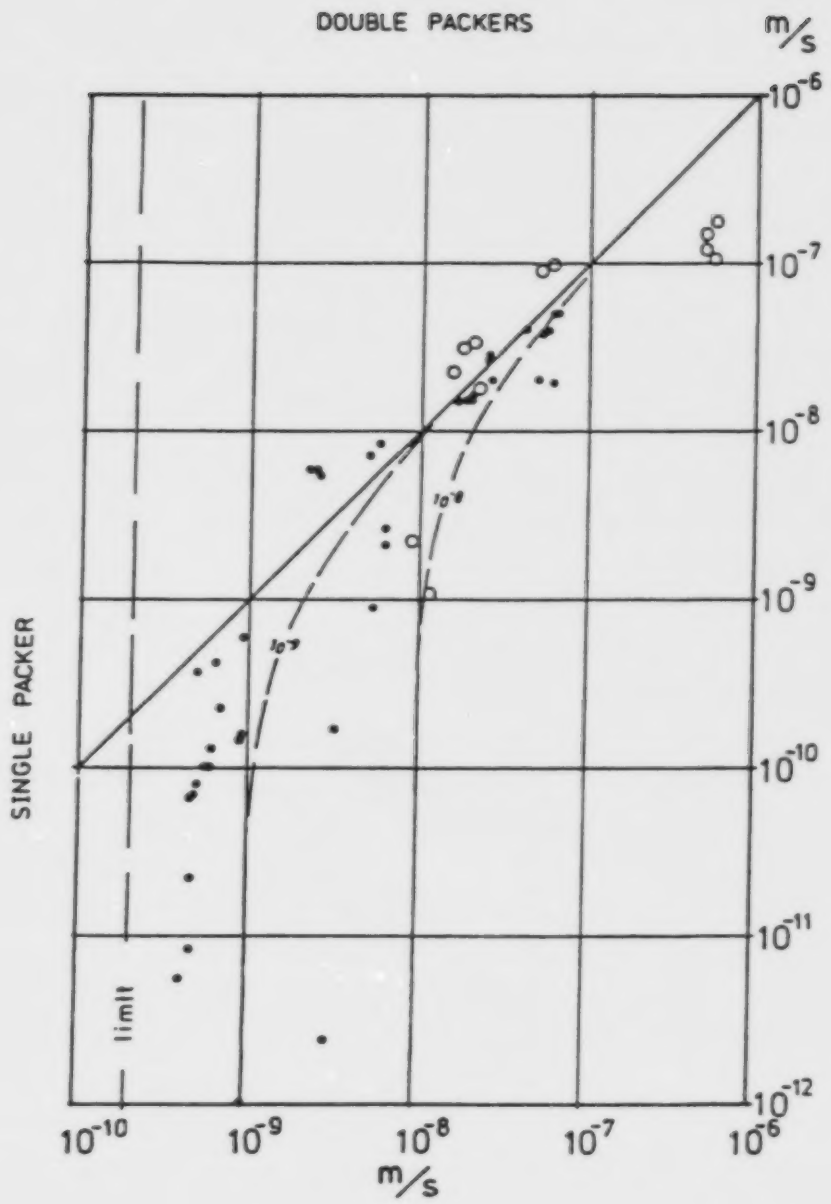


Figure 3.7 Hydraulic conductivity from single packer measurements and corresponding value from double packer measurements. Curves are shown indicating leakages corresponding to hydraulic conductivities of 10^{-8} m/s and 10^{-9} m/s in double packer measurements (after Almen et al., 1981)

Test methods and equipment descriptions were provided in the above papers as well as by Almen et al. (1983) and Ahagan (1983). The borehole testing methods were based on injection testing using single and straddle packers, similar to the pre-1979 testing program. Both transient and steady-state analytical methods were used to determine permeability. Test equipment typically included a set of straddle packers with downhole pressure and temperature measurement and a downhole valve that was lowered either on pipes or a flexible umbilical cable. Flow rate measurement was at surface and had specified ranges of 0.09 $mL \cdot min^{-1}$ to 15.0 $L \cdot min^{-1}$ for the pipe-supported system and 0.3 $mL \cdot min^{-1}$ to 7.0 $L \cdot min^{-1}$ for the umbilical cable-supported system. Test interval lengths were usually 25 m and injection pressures were usually 0.2 MPa (20 m column of water). Given these constraints and conditions, the minimum theoretically detectable hydraulic conductivity was 2×10^{-12} $m \cdot s^{-1}$ and 8×10^{-12} $m \cdot s^{-1}$ for the pipe-supported and umbilical cable-supported systems, respectively. Because of thermal transients at surface, which may have been as much as several degrees Celsius during the course of an injection test, particularly with the 1000 m long umbilical cable and the effect of uncertain packer creep behavior, the lowest reliable flow rate measurement that could be practically realized was likely an order of magnitude larger than the minimum detectable limit of the flow meters. This means that the lowest reliably measured hydraulic conductivity was between 10^{-10} and 10^{-11} $m \cdot s^{-1}$ with a likely error factor of two to three.

Carlsson et al. (1984a,b) and Ahlbom et al. (1983a,b,c,d) provided descriptions of the hydraulic test methods and interpretation of the test data. For flow modeling purposes, the bedrock tested at the Gidea, Kamlunge, Fjallveden and Svartboberget sites was

statistically analyzed to determine effective hydraulic conductivities for different depth horizons and hydraulic conductivity versus depth relations for different sites.

The effective hydraulic conductivity for three-dimensional groundwater flow was calculated as the geometric mean of a log-normally distributed set of hydraulic conductivities based on work by Dagan (1979, 1981) for heterogeneous porous media. There are several assumptions to this approach which are difficult, if not currently impossible, to evaluate and which cast some uncertainty on the validity of the method. These assumptions include:

1) a heterogeneous fractured medium is equivalent to a heterogeneous porous medium;

2) the fractured medium is statistically homogeneous over the horizon of interest and the scale of measurement;

3) the distribution of hydraulic conductivities is log-normal.

The existence of very high hydraulic conductivity zones (macro-permeability fractures) frequently observed in the testing of fractured rocks casts considerable doubt on the validity of the first two assumptions. The validity of the third assumption is largely untested as a result of a paucity of field data.

Hydraulic conductivity versus depth relations were proposed for the field data by Carlsson et al. (1984a) and Ahlbom et al. (1983a,b,c,d) (e.g., see Figure 3.8). Such gross simplifications of hydraulic properties are difficult to justify considering that the hydraulic conductivity of a fractured rock mass results from the complex manner in which individual discontinuous fractures interconnect to form networks for flow. The hydraulic properties of such fracture

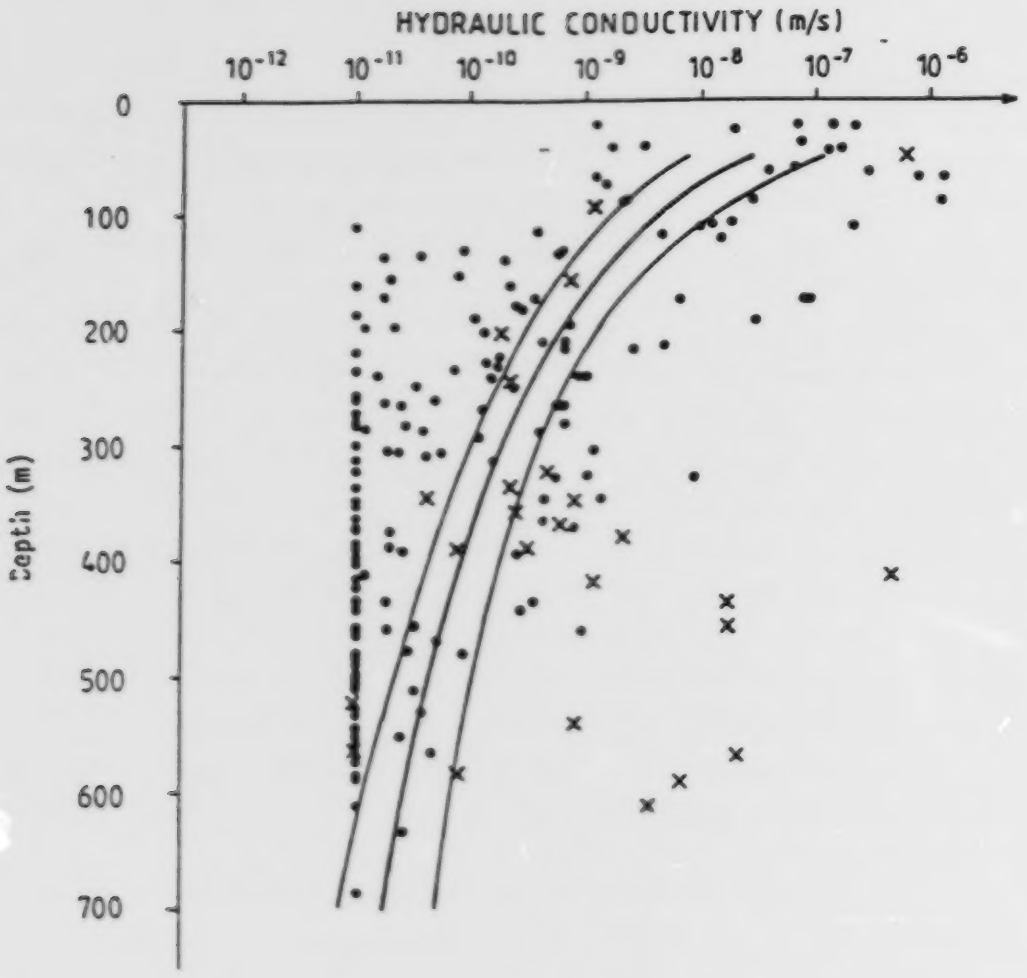


Figure 3.8 Calculated hydraulic conductivity versus depth with a confidence interval of 98% for the rock mass at Fjallveden assuming three-dimensional groundwater flow (after Carlsson et al., 1984a)

networks are strongly influenced by the geometric properties of the fracture system, the geologic and structural history of a particular rock mass and the remnant and current states of tectonic stresses. To suggest that simple hydraulic conductivity versus depth relations exist neglects the importance of geologic and structural framework to groundwater flow systems.

Several studies of the permeability of Swedish bedrock, unrelated to the nuclear waste disposal problem, were described by Carlsson and Olsson (1977a,b), Carlsson and Carlstedt (1977) and Lindblom (1979).

Carlsson and Olsson (1977a,b) described the results of straddle-packer and single-packer injection tests completed in 55 boreholes in various granitic areas of Sweden and analyzed the tests using the steady-state assumption and Moye's shape constant. Only limited descriptions of the test methodology and equipment were provided. Fluid injection pressures of 0.800 MPa (80 m head of water) were reported for the injection tests. As most of the tests were completed at depths of 20 to 75 m, the injection pressures likely exceeded the in situ fluid pressures by factors of two to three. In shallow fractured granite rocks, high fluid injection pressures can be expected to hydraulically open the in situ fractures resulting in overestimation of hydraulic conductivity (Gale, 1977). Carlsson and Olsson (1977b) also determined a line of best fit between hydraulic conductivity and depth (Figure 3.9) when the scatter and reliability of such data clearly did not suggest or warrant such a relation.

Carlsson and Carlstedt (1977) reported hydraulic conductivities of near surface granitic bedrock in Sweden from water well pump tests with means of 2×10^{-7} to 8×10^{-6} $m \cdot s^{-1}$. Lacking any detailed description of test method, these hydraulic conductivities appear reasonable based on similarity of results to those of Carlsson and Olsson (1977b) for similar depths.

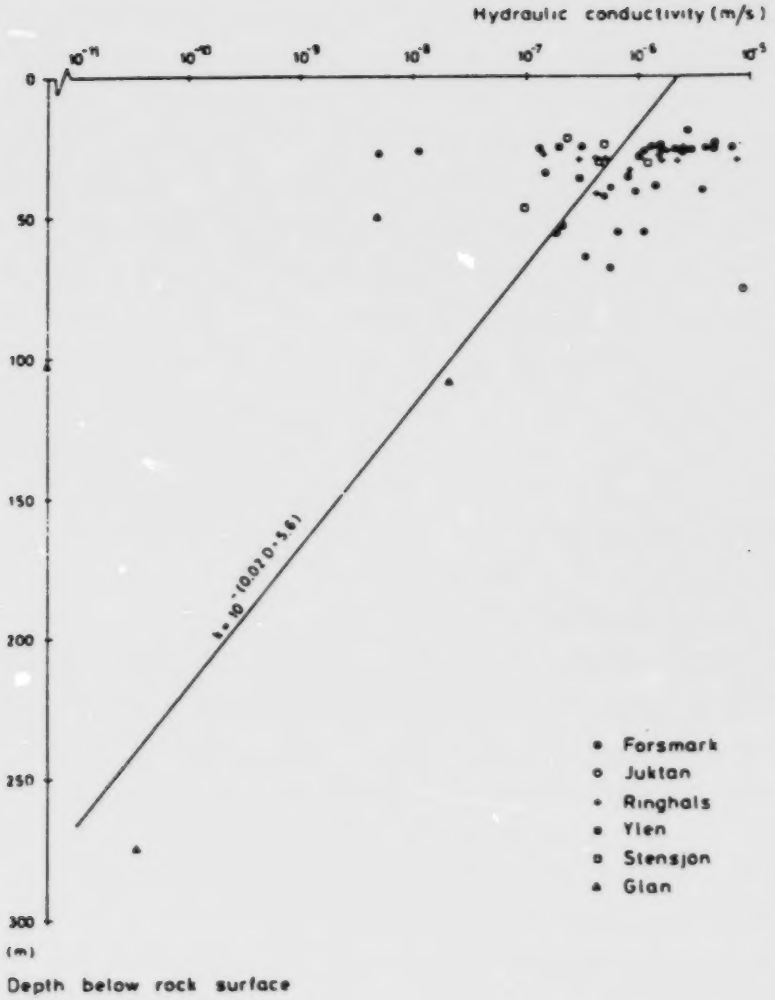


Figure 3.9 Mean borehole hydraulic conductivities (based on water loss measurements) plotted against the vertical depth of respective drill-hole below the rock surface (after Carlsson and Olsson, 1977b)

Lindblom (1979) described an interesting study of the permeability of granitic rock determined from three different methods in the context of investigations for a large underground gas storage cavern at 120 m depth. Hydraulic conductivities were calculated based on inflow to the storage cavern (1×10^{-8} m·s^{-1}), water losses from a water injection curtain (4×10^{-8} m·s^{-1}) and an arithmetic average of injection tests ($1 - 4 \times 10^{-8}$ m·s^{-1}). The described test and analytical methods are judged to be appropriate for the range of hydraulic conductivities described. The similarity between the three hydraulic conductivities suggests that the individual test methods were reliable and that they sampled a uniform and relatively homogeneous rock mass with respect to groundwater flow.

3.2.2 Porosity

Although considerable work has been expended in the characterization of Swedish sites, little of this effort has been directed towards the evaluation of porosity. The measurements of Skagius and Neretnieks (1983, 1986) constitute the majority of the available measurements for Swedish sites. The materials tested were primarily granitic and gneissic cores from Finnsjon, Stripa, Karlshamn, Gidea, Svartboberget, Fjallveden and Studsvik. Skagius and Neretnieks provided a description of the method used for porosity determination and indicated that two separate techniques were employed on each sample. One of these methods was an immersion technique which consisted of measuring the weight difference between saturated and oven dried samples. The second method involved leaching a solution of known concentration from a saturated sample using a known volume of water. The results of the two sets of measurements compared favourably with the majority of measurements being within a factor of 1.5 of each other. Given the usual variation associated with duplicate

measurements using the same technique, the ability to replicate such measurements using different techniques is commendable. Their values ranged from 0.06% to 0.38% for a variety of gneissic and granitic samples.

3.2.3 Fracture Characteristics

The most detailed information describing fracture characterization work at Swedish research areas is contained in Hult et al. (1978) who described the results of oriented television camera surveys conducted at Krakemala, Avro, Finnsjon, Forsmark and Karlshamn. Unfortunately, they merely presented the results of their investigations (as polar plots) and provided little indication as to either its synthesis or its eventual use. Given the errors that may arise from the use of oriented borehole television camera logs (i.e., due to variation in borehole diameter, and difficulties in tracing fractures around the borehole), it would have been useful to compare some of the orientation data obtained by television camera logs with data obtained by other methods (e.g., logging of oriented cores). Hult et al. (1978) did not report any such verification efforts.

Larsson et al. (1977) reported using 4076 fractures to compile a data base of orientations and trace lengths in the western Blekinge area, although specific details regarding the techniques employed were not discussed. Also, the intended application of the data was not reported, rendering an evaluation of its reliability and appropriateness difficult. Similarly, the surface map of fractures and the borehole fracture logs of the Studsvik area presented by Landstrom et al. (1978) are accompanied by insufficient information to permit an evaluation.

Olsson and Ahlbom (1984) described general procedures used to characterize Swedish sites and present limited fracture frequency information from boreholes at Kamlunge and Fjallveden. It would appear

from discussions presented in Olsson and Ahlbom (1984) that the major use of this information was to assist the field investigation program as opposed to the development of a fracture model of the site. Given this application, the type and quality of information reported was appropriate.

3.3 FINNISH SITES

3.3.1 Permeability

Borehole tests to evaluate permeability of Finnish bedrock have been reported at three Finnish sites; Loviisa (Gardemeister and Rouhiainen, 1984), Olkiluoto (Laine and Tikkanen, 1982) and Lavia (Almen and Persson, 1984).

The testing at the Lavia site was performed by Swedish Geological Co. using equipment and methods developed as part of the Swedish standard program for radioactive waste disposal site investigations. The test methods and equipment were similar to those described by Ahlbom et al. (1983a) and Carlsson et al. (1984a) for the umbilical cable-supported probe. Almen and Persson (1984) provided detailed descriptions of the test equipment, methods and results that facilitated an assessment of the reliability of the test data. In general, the hydraulic conductivity data described by Almen and Persson can be assumed to have similar reliability to data described by Carlsson et al. (1984a,b). This means that the lowest reliable hydraulic conductivity was about 10^{-11} $m \cdot s^{-1}$ with a likely error factor of two to three. The reliability of the data is expected to increase with increasing magnitude of the hydraulic conductivity. Because hydraulic conductivities were determined by three methods (transient flow rate response, steady-state assumption during fluid injection and pressure fall-off after injection, see Figure 3.10), the data are probably more reliable than the hydraulic conductivities determined only from the steady-state assumption. However, uncertainty

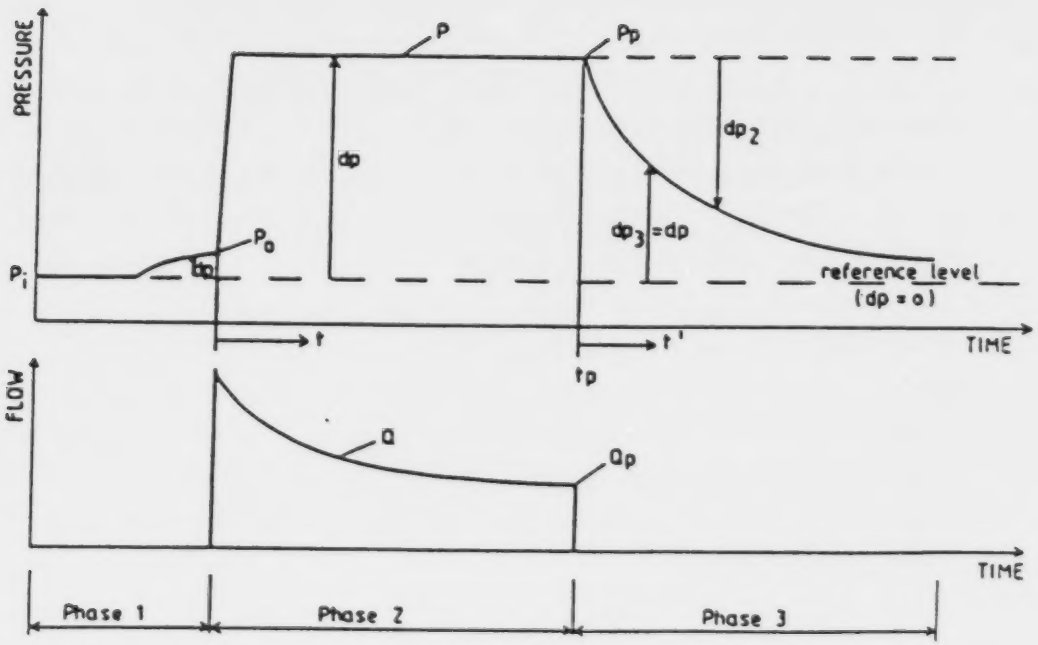


Figure 3.10 General performance of the borehole hydraulic test program in three steps: Phase 1 (packer sealing, Phase 2 (water injection) and Phase 3 (pressure fall-off) (after Almen and Persson, 1984)

in flow field geometry restricts the reliability of any single borehole test result to at best a factor of two. An additional, although not major, source of uncertainty in the method of Almen and Persson was the manner in which formation pressures were determined and therefore differential injection and fall off pressures were calculated. In calculating hydraulic conductivity, the pressure measured five minutes after closing the shut in valve was used as the formation pressure. Because of packer creep and borehole pressure history effects, this value may be in error. For the stated injection pressures (approximately 200 kPa) the likely error associated with this uncertainty is estimated at 10 to 20%.

The permeability data presented by Laine and Tikkanen (1982) for the Olkiluoto site were determined from single-packer and straddle-packer injection tests. As discussed previously for the data of Almen et al. (1981), data from single-packer tests are less reliable than data from double-packer tests. In some of the test results presented by Laine and Tikkanen (e.g., boreholes YD1, YD6), single-packer tests showed high permeability near the bottom of the borehole, which casts considerable doubt on the reliability of the permeabilities which were one to two orders of magnitude less and located at shallower depths than the high permeability zones. These lower permeability horizons may have been overestimated by several orders of magnitude.

The results of straddle-packer injection tests of Laine and Tikkanen had a lower measurement limit for hydraulic conductivity of 5×10^{-10} $m \cdot s^{-1}$. Given the flow measurement limit (0.2 $mL \cdot min^{-1}$), test interval lengths (3.2 m), and injection pressures (100 - 400 kPa), this limit is appropriate provided thermal transients were not excessive (i.e., 1 - 2 °C change over a flow measurement period). As with other injection test results, the data are likely reliable to within a factor of two to three. However, the methods used for calculating hydraulic conductivity from flow rate and injection pressure data were not described.

Only a limited description of test methods and results were provided for the Loviisa site by Gardemeister and Rouhiainen (1984). Single-packer and straddle-packer tests were performed with a measurement range of 10^{-9} to 10^{-5} $m \cdot s^{-1}$. Lacking more detailed information, it is assumed that the data are reliable to within an order of magnitude. More recent and comprehensive tabulation of hydraulic conductivities for the Loviisa site was given by Auttila (1986). Detailed descriptions of test procedures and equipment were not provided.

3.3.2 Porosity

Site characterization studies in Finland have only recently been initiated and the number of porosity measurements reflect this fact. Laine and Tikkanen (1982) reported effective porosities ranging between 2×10^{-5} and 8×10^{-4} for the Olkiluoto site. The values are reportedly based on tracer tests conducted at the site; however, the lack of any information describing the test technique, tracer recovery, etc. prohibits an evaluation of these values. These values are similar to porosity values reported in other programs.

Laine and Tikkanen (1982) also presented porosity measurements of cores. An average value of 2×10^{-3} was reported for tonalite cores whereas an average value of 6×10^{-3} was reported for cores of micaceous gneiss. As with the effective porosity measurements, no detail regarding technique was provided. However, the numbers do appear to be consistent with other reported values.

Gardemeister and Rouhiainen (1984) presented effective porosities of 5×10^{-4}, 2×10^{-3} and 4×10^{-3} for intact bedrock and upper and lower fracture zones at the Loviisa power plant site. Unfortunately, these numbers were calculated based on an

undescribed technique using permeability and fracture spacing. It is unlikely that an effective porosity calculated using such techniques could be used in solute transport calculations.

3.3.3 Fracture Characteristics

Only very limited information was available to describe fracture systems present at the Finnish research areas. The information consisted of surface maps and subsurface fracture densities at Loviisa, as reported by Gardemeister and Rouhiainen (1984), and Olkiluoto as reported by Laine and Tikkanen (1982). Although insufficient information was presented to properly evaluate either set of data, the reported fracture characteristics are not atypical of those reported for similar environments elsewhere.

3.4 NEVADA TEST SITE

3.4.1 Permeability

Permeability values for the Climax granite of the Nevada Test Site were reported from field testing in an underground drift by McMullen and Pasternak (1970), Ballou (1979), Murray (1980) and Isherwood et al. (1981). The underground workings, located at 420 m depth, were originally constructed to support underground nuclear tests in the late 1960s. The rock mass surrounding the underground openings were in various and uncertain degrees of saturation.

Borehole straddle-packer tests (air injection) described by McMullen and Pasternak (1970) were analyzed using two methods that were described only as a flow method and a pressure decay method. The equivalent hydraulic conductivities ranged from 5×10^{-8} to 1×10^{-6} $m \cdot s^{-1}$ and may have reflected the damage due to the nuclear explosion that was less than 200 feet from the boreholes. Thus

although the hydraulic conductivities may be reliable, they may not be representative of natural rock conditions.

Ballou (1979) and Murray (1980) described borehole permeability tests completed in boreholes drilled 9 to 12 m deep in the floor of the drift as part of an in situ heater test. Air permeabilities, calculated using a pulse-pressure transient method were reportedly less than 10^{-9} darcies. This is equivalent to hydraulic conductivities of less than 10^{-14} $m \cdot s^{-1}$. Lacking detailed descriptions of the test equipment and methods, we suspect that hydraulic conductivities in this range may only be accurate to an order of magnitude. Additional uncertainty relates to the effect of saturated/unsaturated conditions on the test data (see Section 3.5.1).

Isherwood et al. (1981) described hydraulic testing of fractures in support of proposed radionuclide migration experiments in the Climax Granite. Prior to hydraulic testing, filtered water was injected to water saturate the fractures in the vicinity of the borehole. Transient flow rate-constant pressure injection tests were performed and analyzed using the method of Jacob and Lohman (1952) to estimate transmissivity and parallel plate fracture openings. Fracture openings of 20 m and 30 m were reported by Isherwood et al. These openings are certainly within the range of openings that can be reliably determined by this testing method.

Factors which influenced the reliability of the test results are the uncertain degree of water saturation of the fractures tested and the borehole history effect as a result of attempting to saturate the fracture.

In summary, the permeability data for the Climax Granite are of limited reliability and representativeness. Although some test results may be reliable, they are few in number and therefore most of the data do not provide a representative measure of the permeability of naturally fractured, fully saturated crystalline rocks.

3.4.2 Porosity

Maldonado (1977) summarized numerous measurements made on granite samples from the Climax Stock at the Nevada Test site. Values ranged from 6×10^{-3} to 1×10^{-2}. No description of the test method was given although the numbers appear to be reasonable.

3.4.3 Fracture Characterization

Thorpe and Springer (1981) reported the results of their fracture mapping conducted at the 420 m level in the Climax Stock. Their work was conducted primarily for the purpose of identifying candidate fractures for radionuclide migration experiments. As such, the criteria used for the selection of fractures were geared towards major features. The criteria included:

1. Fractures or zones of fractures that could be traced along both sides and the ceiling of the drift;

2. Features that were parallel or nearly parallel to the drift and extended for a distance equal to approximately twice the width of the drift;

3. Features that appeared strong enough to meet the previous criteria but were truncated by another feature.

Obviously such subjective criteria will introduce a significant bias into the samples of the fracture population obtained as part of this work. In addition, biases associated with the orientation of the drift will also be present. The method described by Thorpe and Springer (1981) used to establish dip angles is probably only accurate to $\pm$ 10°. Thorpe and Springer (1981) found

significantly different orientations of the major features mapped in the main drift compared to the tail drift. While they indicate that the difference in drift orientation (and consequently the bias associated with it) could not account for their findings, it is quite possible that the highly subjective nature of their selection criteria may be a factor in their findings. Wilder and Patrick (1980) conducted an earlier mapping of the tail drift and determined a predominant orientation not unlike that of the main drift.

Thorpe (1984) presented the results of a fracture characterization study performed for subsurface borehole UG-2. Both fracture density and orientation data were presented although no use for the collected data was suggested. Without some knowledge of how this information will be used, it is difficult to assess either its suitability or reliability.

Wilder and Yow (1984) summarized the fracture characterization studies performed in the Climax Stock including mapping in the underground drifts as well as core logging of boreholes. Again the ultimate use of this data was not described making an assessment of its usefulness difficult. Wilder and Yow (1984) did attempt two different correction procedures to account for biases introduced by the drift and borehole orientations. One technique was basically a trigonometric correction (i.e., the Terzaghi correction (Terzaghi, 1965)) made to ensure that equally spaced fractures would be treated the same regardless of the angle of intersection. The major difficulty with this approach is that random features that are oriented in a near parallel direction are poorly represented. The other correction technique employed by Wilder and Yow (1984) was termed an additive or normalizing correction and consisted of pooling data from boreholes (drifts) of different orientation to cover blind zones. Boreholes of different lengths were normalized to a common length. A number of difficulties may also be associated with this approach. For example, unless the boreholes are orthogonal, biases in the areal

coverage may still exist (even though no blind zones exist). In addition, the normalizing procedure automatically assumes that the fracture characteristics along a borehole do not change, an assumption that was not verified by Wilder and Yow (1984).

3.5 COLORADO SCHOOL OF MINES - OCRD Room

3.5.1 Permeability

Montazer and Hustrulid (1983) described the equipment, methods and results of steady-state air injection and water injection tests, and transient pressure pulse and decay (fall-off) tests performed at the OCRD test room by personnel of the Colorado School of Mines. The OCRD test room is located 100 m below ground surface in unsaturated biotite hornblende gneiss.

The test equipment described by Montazer and Hustrulid is similar to test equipment described by Gale (1981) and Forster and Gale (1980) that was used in the Stripa project. A significant improvement in the equipment, however, was the use of a guarded or quadruple packer probe for detecting leakage around packer seals or through the rock parallel to the borehole axis. The vast majority of the test results described by Montazer and Hustrulid are from air permeability tests using constant pressure injection or pressure decay. Montazer reported hydraulic conductivities from the air permeability tests that generally ranged from 10^{-10} m·s^{-1} to 10^{-5} m·s^{-1} with some values close to the drift face of greater than 10^{-5} m·s^{-1}. The hydraulic conductivities are subject to several sources of uncertainty that may reduce their reliability. The first source of uncertainty relates to the representativeness of the higher hydraulic conductivities. Many of the very high hydraulic conductivities (greater than 10^{-4} m·s^{-1}) were determined within a few metres of the drift face and therefore were likely subject to stress redistribution and permeability enhancement as a consequence of

excavation. A second source of uncertainty relates to the manner in which air permeability data were expressed as hydraulic conductivity data.

In flow of gases through permeable media at small pressures, the fluid velocity is not zero at the walls of the pores as is the requirement for Darcy's law. An empirical relation between Darcian permeability, k, and the permeability of a compressible fluid, k_c, such as air, has been observed and is known as the Klinkenberg effect (Montazer and Hustrulid, 1983):

$$k = k_c/(1 + B/p) \qquad (3.1)$$

where: p is pressure and B is an experimentally derived constant characteristic of both the gas and the medium. Equation (3.1) shows that hydraulic permeability will always be less than air permeability and that air permeability will be inversely and linearily proportional to applied test pressure. The majority of the test results of Montazer and Hustrulid do not show such an inverse linear relation. Because of this and the uncertainty in the B parameter, the Klinkenberg effect was ignored in calculation of hydraulic permeabilities. The calculated hydraulic permeabilities and conductivities are therefore overestimated by an uncertain amount for each test.

In addition to the above uncertainties in calculated hydraulic conductivities, Montazer and Hustrulid identified partially saturated fracture flow conditions as a possible explanation for some of the observed permeability-pressure relations. The existence of these conditions casts doubt on the reliability of the calculated hydraulic conductivities as the hydraulic conductivity of fractures can be expected to be a function of the degree of saturation.

In summary, although many of the results described by Montazer and Hustrulid show repeatability (up to three retesting sequences) the reliability of the calculated hydraulic conductivities was not established. We suspect that problems associated with partial saturation and differences between air and hydraulic permeabilities make the test results only reliable to within an order of magnitude with overestimation of hydraulic conductivity being more likely than underestimation.

3.5.2 Porosity

No data describing porosity measurements for the OCRD room were found in the literature reviewed.

3.5.3 Fracture Characterization

Hutchinson (1983) summarized the results of surface mappings conducted in the vicinity of the CSM by several investigators including Moench et al. (1962), Harrison and Moench (1961), Sims et al. (1959), Badgley (1959) and Hutchinson (1958, 1959, 1960, 1972, 1976). Major lineament types and directions were summarized and a regional tectonic map showing major structural features was presented. Hutchinson (1983) did a reasonable job at postulating the tectonic events responsible for the observed features. How these features relate to groundwater flow and whether these fractures extend to depth was not addressed.

3.6 SAVANNAH RIVER

3.6.1 Permeability

Marine (1966, 1967, 1979 and 1981) described the results of laboratory and field testing for estimation of bedrock permeability at the Savannah River Plant, Aiken, South Carolina. Laboratory tests were performed on core samples of bedrock (a schist and gneiss with lesser amounts of quartzite). Borehole tests for permeability estimation included slug injection and withdrawal tests using straddle packers, long-term pump tests, a two-well tracer test and groundwater sampling for helium age dating. Marine (1981) concluded from these studies that there exists essentially two types of permeable crystalline rock beneath the Savannah River plant: a "virtually impermeable" rock ($K \approx 2 \times 10^{-10}$ $m \cdot s^{-1}$) comprised of intact and sparsely fractured rock and a "hydraulically transmissive" rock ($K \approx 2 \times 10^{-7}$ $m \cdot s^{-1}$) comprised of highly fractured zones.

The permeability of the "virtually impermeable" rock was measured using constant head injection tests on intact cores (lower test limit of 3.8×10^{-13} $m \cdot s^{-1}$) and from in situ straddle-packer tests (lower test limit of 9.4×10^{-12} $m \cdot s^{-1}$). These lower test limits are consistent with similar test limitations described in other investigations. However, because of uncertain flow geometry, packer leakage and borehole pressure history effects, the lower hydraulic conductivity values (about 10^{-11} $m \cdot s^{-1}$) determined from the straddle-packer tests are likely only reliable to within an order of magnitude. The intact core estimates of permeability likely have greater reliability because of better controlled experimental conditions. However, the laboratory tests were subject to stress relief that may have resulted in overestimation of the permeability of "virtually impermeable" rock.

The permeability of "hydraulically transmissive" rock was determined from pumping tests ($K \approx 3 \times 10^{-7}$ m·s^{-1}), from a tracer test ($K \approx 2 \times 10^{-7}$ m·s^{-1}) and from radiogenic helium age dating of groundwater samples ($K \approx 2 \times 10^{-9}$ m·s^{-1}). The results of the pumping test and tracer test are individually reliable and because of their consistency are thought to be representative for the particular section of "hydraulically transmissive" rock tested. In contrast, the hydraulic conductivity determined from analysis of groundwater ages assuming an effective porosity, flow path length and hydraulic gradient are inconsistent with the results of the pumping tests and tracer test, being about two orders of magnitude smaller. The lower hydraulic conductivities determined using radiogenic helium age dating and assumed hydrodynamic conditions are much less reliable than the other two estimates. In addition to difficulties associated with attempting to estimate flow path length and effective porosity over large distances, the helium age dating method requires detailed information on the distribution of radiogenic helium producing elements U and Th and associated rock porosities. Andrews et al. (1982) indicated that it is not possible to use the radiogenic helium method to calculate groundwater age directly and that the attempts by Marine (1979) to make such age estimates may have overestimated the groundwater age. Fritz (1982), in a general statement on age dating using isotope methods, indicated that absolute age dating as is done for solid rocks is not possible for groundwaters. Given these uncertainties, the hydraulic conductivity calculated by Marine (1979) from radiogenic helium contents is not reliable.

The estimates of rock hydraulic conductivity for the "virtually impermeable" rock (average $K = 2 \times 10^{-10}$ m·s^{-1}) are comparable to results from similar depth (300 - 400 m) investigations in cyrstalline rock reported for the Stripa mine and other Swedish sites. Although the similarity between this Savannah River Plant data and other data for crystalline rocks does not prove the reliability of the data, it does show that the results are

consistent and within an order of magnitude range of other reliable test program results.

3.6.2 Porosity

Marine (1979) reported porosity values of crystalline rock cores determined by the U.S. Corps of Engineers at the Savannah River Plant near Aiken, S.C. These values ranged from 6×10^{-4} to 1.9×10^{-3} with an average value of 1.3×10^{-3}. No information describing the test method or technique was given. The numbers do appear to be reasonable in comparison with other values reported in the literature.

Webster et al. (1970) reported a single effective porosity value of 8×10^{-4} as a result of a tracer test conducted at the site. Although the analysis of the breakthrough concentration ignored matrix diffusion, the value is probably order of magnitude correct.

3.6.3 Fracture Characteristics

Marine (1979) presented limited data on the fracture characteristics of the deep crystalline rock at the Savannah River plant. The information consisted primarily of fracture density data (i.e., fracture location) obtained from geophysical and core logs performed on wells DRB 2, 5, 6, and 7. The reason for running these logs was primarily to identify highly transmissive fractures. As such, the data collected are probably suitable, although as Marine (1979) pointed out, many deflections on the geophysical logs indicated differences in rock properties that were unrelated to the presence of open fractures. Marine's (1979) data are, however, inadequate to perform a three-dimensional fracture characterization of the crystalline rock since all data were obtained from vertical boreholes (thereby biasing the sample). In addition, more parameters such as trace length, aperture estimates, are required to properly characterize the system.

3.7 ORACLE SITE

3.7.1 Permeability

Permeability data for the Oracle site were reported primarily by Hsieh et al. (1983) and subsequently with interpretations by Jones et al. (1985), Hsieh et al. (1985), Hsieh and Neuman (1985) and Neuman et al. (1985).

Hsieh et al. (1983) performed open borehole slug tests, straddle-packer injection tests, pressure-pulse tests and hydraulic interference tests. The equipment, methods and limitations of these different hydraulic test programs were described in detail by Hsieh et al. (1983) and readily allow assessment of the reliability of the calculated permeabilities.

The open borehole slug tests were performed in four relatively shallow boreholes (about 60 - 70 m depth) and yielded similar hydraulic conductivities of $1\text{-}3 \times 10^{-8}$ $m \cdot s^{-1}$. Because the method of applying the slug was relatively instantaneous (required about 20 s) compared to the duration of the tests (about 10 h) and the data fit to type curves was good, the calculated hydraulic conductivities are likely reliable to within a factor of two.

More complex equipment and test procedures were used to complete the straddle-packer injection and pressure-pulse tests in four single boreholes. These tests were completed using air-inflated straddle packers with three downhole pressure transducers, a downhole temperature thermister, a downhole valve and surface flow rate measuring equipment (constant head flow tanks of different diameter).

The pressure transducers were used to monitor pressure within the injection test interval and above and below the test interval. The monitoring of pressure above and below the test interval was conducted

in an effort to define leakage of injection fluid to these zones. As Hsieh et al. (1983) indicated, leakage was observed in many of the tests and was a major problem at the Oracle site, probably as a result of the abundance of vertical fractures identified at the site. Although pressure monitoring above and below the straddle packers can detect some instances of leakage, the method is not sensitive to small leakage flow rates and a guarded or quadruple packer assembly is preferred for such applications. The limitations of leakage detection using only pressure monitoring above and below a straddle-packer assembly result from the potentially large pressure transients that may naturally occur in the monitoring intervals and may mask pressure transients caused by packer leakage. For example, when straddle packers are inflated in a borehole drilled into a recharging groundwater flow system, the natural flow of groundwater down the borehole from high hydraulic head zones to low hydraulic head zones is interrupted and a rising and falling pressure transient will be imposed in the monitoring intervals located above and below the test interval, respectively. Furthermore, assuming steady-state conditions are achieved in these monitoring intervals prior to injection, a high permeability zone situated in either interval may effectively "take" all leakage fluid with negligible pressure increase.

Thus although Hsieh et al. (1983) reported leakage to upper and lower test intervals for tests completed in two boreholes, the reliability of these leakage measurements is suspect. For example, it is not clear how a reliable measure of fluid leakage to lower intervals of borehole H-2 from intervals with hydraulic conductivity of 10^{-9} $m \cdot s^{-1}$ can be obtained when the bottom of the borehole has hydraulic conductivity of 6×10^{-6} $m \cdot s^{-1}$. The flow rate-injection head properties of this deep, high-permeability zone (2000 $mL \cdot min^{-1}$ at 1 m head) would only generate head increases of 0.005 and 0.05 m head for leakage flow rates of 10 and 100 $mL \cdot min^{-1}$, respectively. As the hydraulic heads were only reported to 0.1 m, it is not certain that packer leakage could be reliably identified in this

situation. Also because packer by-pass or leakage was a potential problem at this site, the low hydraulic conductivities reported may be unreliable. For example, many of the test intervals in borehole H-2 had injection flow rates of less than 100 $mL \cdot min^{-1}$ which, considering the flow rate-injection head properties of the deep high-permeability zones, could be entirely undetected fluid leakage.

An alternate method of quantifying the importance of fluid leakage is to sum the transmissivities determined from individual packer injection tests and to compare this result to an open borehole or full borehole hydraulic test. Hsieh et al. (1983) carried out such a comparison for two boreholes and observed similar transmissivities within a factor of two from open borehole slug tests and steady-state analysis of packer injection tests. Hsieh et al. concluded from this comparison that the results of the open borehole slug tests and the packer injection tests are consistent with one another. This conclusion, however, is only appropriate to the high transmissivity sections of the borehole as the low transmissivity (and hydraulic conductivity) intervals contribute negligibly to the total borehole transmissivity.

Hsieh et al. (1983) also conducted pressure-pulse tests or pressurized slug tests in many test intervals for comparison with injection test results. The hydraulic conductivities were determined from the type curve method of Bredehoeft and Papadopulos (1980) with test interval compressibility determined from calibration in an impermeable test interval (the well casing). The comparsion is illustrated in Figure 3.11. Figure 3.11 shows that in general, the hydraulic conductivities determined from the pressure-pulse tests underestimated the hydraulic conductivities determined from steady-state injection tests by up to an order of magnitude. Hsieh et al. (1983) interpreted this difference to be due to the fact that injection tests generally sample larger volumes of rock than pressure-pulse tests and that larger volumes are likely to include zones of higher permeability. There is, however, sufficient detail in the test results presented by Hsieh et al. (1983) to obtain a more plausible explanation for the differences in calculated hydraulic conductivity.

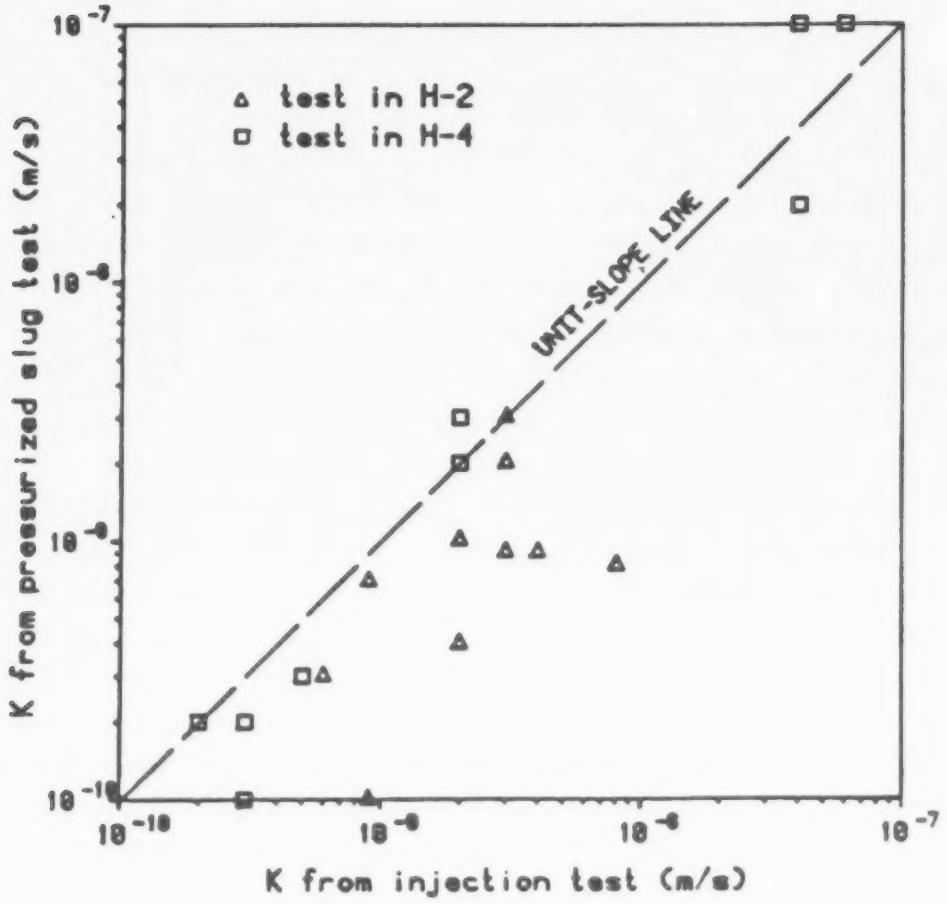


Figure 3.11 Comparison between hydraulic conductivities determined by pressure-slug tests and steady-state analyses of injection tests (after Hsieh et al. 1983)

The hydraulic conductivities were calculated from the pressure-pulse tests using a test interval compressibility determined from a single calibration in the steel casing of each borehole. Because of different inflation methods and pressures and possible air leakage during each inflation and setting of packers, the test interval compressibility is not likely to be identical for each test interval. This is in fact the case, as the test interval compressibilities, based on the magnitude of the applied pressure-pulse, are extremely variable showing up to five-fold variations. Detailed inspection of the test data of Hsieh et al. (1983) further shows that the underestimation of hydraulic conductivity shown in Figure 3.11 results for the most part from underestimation of test interval compressibility. All the pressure-pulse tests that underestimated hydraulic conductivity showed lower magnitude pressure pulses and therefore higher compressibility of the test interval than for the single calibration test conducted in the steel casing. If Hsieh et al. (1983) had used test interval compressibilities determined for each test from the measured magnitude of the pressure pulse, the correlation between test results would be much better than indicated in Figure 3.11. Because of the variation of test interval compessibilities, the hydraulic conductivities reported by Hsieh et al. (1983) from pressure-pulse tests are underestimated by up to a factor of five relative to steady-state hydraulic conductivities.

However, because of problems associated with packer leakage and uncertain flow field geometry, the absolute reliability of single borehole hydraulic conductivities is generally similar to that of most other programs. For hydraulic conductivities above about 10^{-9} $m \cdot s^{-1}$, the injection test results are reliable to within a factor of three. Below 10^{-9} $m \cdot s^{-1}$, the hydraulic conductivities have uncertain reliability.

Hsieh et al. (1983), Hsieh and Neuman (1985) and Hsieh et al. (1985) also conducted hydraulic interference tests and developed an analytical method for determining the anisotropic hydraulic

conductivities of an equivalent porous media. From their hydraulic interference tests and analyses, Hsieh et al. (1985) concluded that the Oracle granite behaved as a near-uniform anisotropic medium (at the test scale of 10 m), the hydraulic conductivity of which was strongly controlled by the orientations of the major fracture sets. The principal hydraulic conductivities determined from the interference tests completed between three boreholes varied from 2×10^{-8} to 2×10^{-7} $m \cdot s^{-1}$. The conclusions of Hsieh et al. (1985) are important because they represent the first well-documented case of apparent anisotropic continuum behavior for a fractured crystalline rock. The results of Hsieh's work, however, are subject to some uncertainties that influence the reliability of the conclusions.

Hsieh's hydraulic interference tests were conducted with only the injection and monitoring intervals isolated by straddle packers. The remaining sections of the injection and monitoring boreholes and the six other boreholes were left open. These open sections of borehole likely influenced the hydraulic response observed in the monitoring interval in an uncertain and complex manner, as observed in the experiments reported by Lundstrom and Stille (1978) in the Stripa mine. The possible extent of this effect may be determined from the hydraulic conductivity plots used by Hsieh to demonstrate anisotropic continuum behavior (Figure 3.12). If the hydraulic conductivity data plot as an ellipsoid, then the rock mass is assumed to behave as an anisotropic continuum. The data from three sets of interference tests between borehole pairs and the fitted ellipses are shown in Figure 3.12. The fits we believe, are not unambiguous particularly for test series B and C. The best fits as indicated by Hsieh et al. (1985) were for test series A. Test series A was also completed between the two closest spaced boreholes, where we expect the hydraulic influence of adjacent open boreholes would be minimal. The poorest fit was obtained for test series C from borehole H-2 to H-6. Borehole H-6 was located in the centre of the eight borehole array and could be expected to show the greatest influence from surrounding open boreholes. From

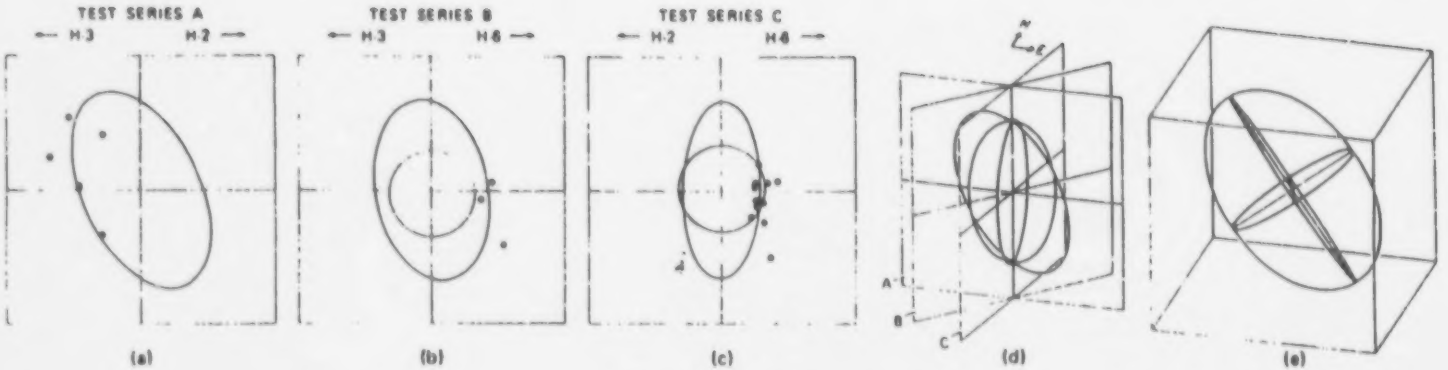


Figure 3.12 Directional hydraulic conductivity ellipsoid fitted by ordinary least squares; (a-c) Vertical cross-sections of fitted ellipsoid along planes of test series A, B and C; (d) Oblique view of vertical cross sections oriented in three dimensions; (e) Oblique view of fitted ellipsoid (after Hsieh et al., 1985)

INTERA

this discussion and other details of the test program, we believe that the conclusion of near uniform anisotropic continuum behavior is overstated. Certainly, however, the data are an important first step in assessing the permeability characteristics of fractured rocks, but the test results should be interpreted with caution.

Corroborating evidence for the validity of the interference test results of Hsieh et al. (1985) are found in the fracture mapping data and the results of single borehole tests. Hsieh et al. (1985) observed that the major principal hydraulic conductivity was aligned with the intersection line of the two primary fracture sets as one might expect. Furthermore, the geometric mean from 100 packer tests in individual boreholes was very close to the minimum principal hydraulic conductivity determined from the interference tests. Although Hsieh et al. (1985) did not indicate whether the packer tests are injection tests (reliable) or pressure-pulse tests (unreliable), the results seem consistent.

In summary, it appears that the magnitude of the hydraulic conductivities determined from the single borehole injection tests and the interference tests are likely reliable to within a factor of two to three. However, given the ambiguity of the ellipsoid fits and the above uncertainty factor, the determination of principal hydraulic conductivities that differ by ratios of 2:3:1 is likely not warranted.

3.7.2 Porosity

Jones et al. (1985) reported a number of porosity measurements resulting from a variety of different measurement techniques. These techniques included in situ measurements on a single borehole as well as laboratory measurements on eighteen cores taken from the same borehole. In situ methods included such geophysical techniques as neutron and acoustic logs while the laboratory method consisted of performing density measurements on bulk samples and grains using a pycnometer.

Jones et al. (1985) attempted to establish hydrogeological parameters through the use of a variety of techniques. In their study, Jones et al. attempted to show a correlation between the laboratory measurements on cores taken along the borehole with the response from a neutron logging survey conducted in the same borehole. Their results were disappointing, with a plot of core porosity versus neutron log response showing considerable scatter. A second plot of acoustic log porosity versus measured core porosity demonstrated the same wide scatter. A number of points should be made in discussing the data obtained using these techniques. First of all, the values obtained from all three methods were quite high, typically between 1% and 6%. Comparable measurements performed on quartz monzonites or similar rocks elsewhere may be up to an order of magnitude lower. The reason all three methods may have had such high values is that the results of the geophysical surveys may have been based on calibration to the laboratory data. The question then arises as to the reliability of the core measurements. Without a detailed description of the test procedure, it is difficult to assess the reliability of their numbers. However, a few statements can be made regarding this technique. Generally, indirect measurement techniques (e.g., one which uses one parameter measurement to calculate or infer another) are less accurate than direct measurement techniques. This is due to the fact that an empirical or theoretical relationship must be used to relate the measured parameter value to the desired quantity. Some error will be associated with the use of such a relationship since in practice neither theoretical nor empirical relationships are capable of reproducing exactly all observed data. The pycnometer technique is also subject to other sources of error. Destructive test methods, such as employed by this technique, may result in a change of material structure or a loss of material due to fragmentation. Due to the small porosities involved, the loss of even a small amount of material (e.g.,

as rock flour dust) may result in significant errors in the porosity estimate. Another disconcerting observation can be made of the porosity estimates reported by Jones et al. (1985). Their plot of acoustic log porosity versus laboratory value, showed a variation in the latter of up to 5% for the same acoustic log value. The magnitude of this variation is significantly larger than the typical magnitude of most porosity measurements.

3.7.3 Fracture Characteristics

Jones et al. (1985) presented the most extensive information describing fracture characteristics of the Oracle granite. The major sources of this information included surface maps, cores and acoustic televiewer logs. As discussed earlier, fracture information obtained from surface maps will be biased to steeply dipping fractures whereas vertical borehole information will be biased to horizontal or sub-horizontal fractures. Surface fracture maps are further subject to significant noise since many of the smaller fractures may be enlarged by weathering and caused by exfoliation as opposed to structural events. Jones et al. (1985) used the acoustic televiewer log to orient the core and consequently these methods were not used to independently verify fracture orientations. Jones et al. (1985) tried to establish patterns in the fracture parameters they observed and correlate fracture sets to structural events. In doing so, however, Jones et al. (1985) deliberately removed certain observed fracture sets on the justification that they had random orientations. While this may be the case, such fractures may be just as significant hydraulically as those that can be correlated to specific structural events and from a hydrogeological point of view such a filtering of the data would be unjustified. For the Jones et al. (1985) analysis (i.e., correlation of the fracture system to specific structural events) such action may be justified.

3.8 BASALT WASTE ISOLATION PROGRAM

3.8.1 Permeability

Permeability data for the Basalt Waste Isolation Projects (BWIP) at Hanford, Washington were described by Rockwell (1982), Gephart et al. (1984), Thorne and Spane (1983), and Spane and Thorne (1985).

Rockwell (1982) provided an overview of the hydraulic test methods and equipment used at the Hanford site to evaluate the permeability of the Columbia River Basalts. Single packers and straddle packers lowered on a drill tubing with downhole pressure and temperature measurement devices and a downhole shut-in valve were used in the majority of hydraulic tests completed at Hanford. Pump tests, slug tests, pressure-pulse tests and constant head injection tests were used, depending upon the transmissivity of the test interval. Single-packer tests were usually conducted during the drilling as drill stem tests, while straddle-packer tests were performed after completion of drilling. The guidelines for application of different test methods at the Hanford site are summarized in Figure 3.13 from Rockwell (1982). The ranges of transmissivity for each of the five test methods identified in Figure 3.13 appear reasonable with the exception of the test limits for the injection tests. It is doubtful that injection tests can reliably measure transmissivities at or below about 10^{-10} $m^2 \cdot s^{-1}$. For example, with reasonable injection pressures of 0.5 MPa, a transmissivity of 10^{-14} $m^2 \cdot s^{-1}$ requires a flow rate measurement capability of 3×10^{-5} $mL \cdot min^{-1}$. Without detailed temperature measurements, it is unlikely that the lower measurement limit for flow rate would be less than 0.1 $mL \cdot min^{-1}$. Given these constraints, it is also likely that the upper measurement limit for transmissivity is greater than 10^{-9} $m^2 \cdot s^{-1}$.

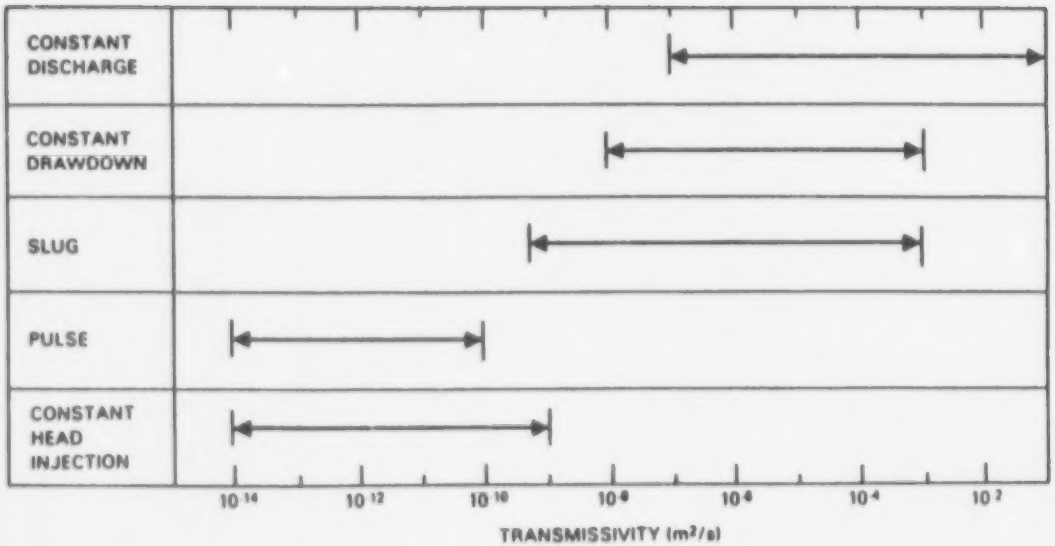


Figure 3.13 Guidelines for application range of test methods for test zones at the Hanford site (after Rockwell, 1982)

Rockwell (1982) reported hydraulic conductivities that ranged from 10^{-11} to 10^{-3} $m \cdot s^{-1}$. The hydraulic conductivities reported by Rockwell are only given in order of magnitude terms (e.g., 10^{-5}, 10^{-6}, 10^{-7} $m \cdot s^{-1}$). Given these order of magnitude estimates and lacking further details on individual test methodologies, the hydraulic conductivities are likely reliably reported. Some uncertainty may exist to hydraulic conductivities below 10^{-11}, but there were only a limited number of these results reported.

Subsequent work by Thorne and Spane (1983), Gephart et al. (1984) and Spane and Thorne (1985) reported hydraulic conductivity measurements from lower permeability basalt flow interiors. In these test programs, hydraulic conductivities were determined using pressure-pulse tests, constant-pressure injection tests and for higher permeability intervals, slug tests. Similar test equipment was used in these field testing programs as was described by Rockwell (1982). Thorne and Spane (1983) report hydraulic transmissivities from different tests that were within a factor of two of each other for test intervals with hydraulic transmissivity between 10^{-8} and 10^{-5} $m^2 \cdot s^{-1}$. For the test interval lengths of 5 - 30 m, these transmissivities correspond to hydraulic conductivities of between 3×10^{-10} $m \cdot s^{-1}$ and about 1×10^{-4} $m \cdot s^{-1}$. The consistency in calculated transmissivity using various test methods suggests that the results are reliable to within the observed range of variability (i.e., factor of two).

Spane and Thorne (1985) also presented a comparison of hydraulic testing methods for measurement of the hydraulic conductivity of low permeability rocks at Hanford. They reported hydraulic conductivities determined from different test methods (pressure-pulse tests and constant-head injection tests) that were within a factor of three for an average hydraulic conductivity of 1×10^{-11} $m \cdot s^{-1}$. Using Hvorslev's shape factor, quoted minimum injection

pressure of 115 kPa, test interval length of 24.7 m and r_b of 3.05 m, the hydraulic conductivity of 1×10^{-11} $m \cdot s^{-1}$ requires flow rate measurement capability of 0.24 $mL \cdot min^{-1}$. This flow rate measurement capability can be attained in carefully monitored test programs and suggests that hydraulic conductivities determined from the injection tests using the steady-state assumptions were as reliable as results from other test programs, to within a factor of two. While the injection tests results were consistent for several different injection pressures, the hydraulic conductivities determined from the pressure-pulse tests showed greater variability (up to a factor of 6.9). Spane and Thorne (1985) analyzed their pressure-pulse tests using the type curve method of Bredehoeft and Papadopulos (1980) sometimes with and sometimes without a measured test interval compressibility. The greater variability of the results of the pressure-pulse tests were recognized by Spane and Thorne as being attributable to their inability to accurately measure the test interval compressibility. More accurate measures of this parameter would theoretically result in more accurate and less variable hydraulic conductivities.

3.8.2 Porosity

No porosity estimates of the BWIP basalts were encountered in the literature reviewed.

3.8.3 Fracture Characteristics

Only very limited fracture characteristic data were encountered for the BWIP site. These included a reported fracture density range of one to thirty per metre (Gephart et al., 1984) as well as some dominant strike directions for specific fracture zones. Without additional information describing the techniques used to gather the data or its eventual use, it is difficult to assess its quality.

3.9 AECL's UNDERGROUND RESEARCH LABOROATORY

3.9.1 Permeability

Permeability data for AECL's Underground Research Laboratory (URL) were reported by Davison (1982, 1984, 1985), Davison et al. (1982) and Davison and Simmons (1984).

Davison (1982, 1984) reported hydraulic conductivities from single-borehole response tests that ranged from 10^{-14} to 10^{-4} $m \cdot s^{-1}$. Davison (1985) also reported hydraulic diffusivities (hydraulic conductivity divided by specific storage) from hydraulic interference tests that ranged from 6×10^{-1} to 2×10^{3} $m^2 \cdot s^{-1}$. Davison (1984, 1985) further reported on the spatial variability and anisotropy of hydraulic conductivity in two of the high permeability fracture zones intersecting several boreholes at the URL site.

Although Davison reported a wide range of hydraulic conductivity at the URL site (10^{-14} to 10^{-4} $m \cdot s^{-1}$) from single-borehole tests, he did not provide details as to testing equipment, testing methodology, or analytical techniques. Without descriptions of these components of the hydraulic testing program, it is almost impossible to evaluate the reliability of the reported hydraulic conductivities.

Furthermore, it is not clear whether the single-borehole response tests were pump tests, constant-pressure injection tests, slug tests, or pressure-pulse tests. No descriptions of test equipment or test conditions were given for any of the reported hydraulic conductivities. This lack of description of test equipment, methods and analytical techniques is anomalous in comparison to other hydraulic test programs reviewed in this report. The data from single-borehole tests do, however, appear consistent with other values reported from

other programs, although hydraulic conductivities below 10^{-12} $m \cdot s^{-1}$ (values of 10^{-14} to 10^{-12} $m \cdot s^{-1}$ are reported) even for long test intervals are likely of questionable reliability.

The permeability characteristics of two extensive fracture zones were also described by Davison. Again, it is not clear how spatial variability of hydraulic conductivity was determined. Davison (1985) only stated that the results of single-packer tests, drilling observations and large-scale hydraulic tests revealed the described permeability conditions. Because the permeability conditions of the fracture zones were shown by Davison to be anisotropic and highly heterogeneous, there would be some uncertainty in permeability calculated from interpretations of hydraulic tests that assume ideal conditions (i.e., homogeneous, isotropic, infinite areal extent, etc.). A case in point are the hydraulic diffusivities reported by Davison (1985). Although no testing or analytical methods for these tests were described, we suspect that the results were determined using methods described previously by Davison (1981). These methods assume ideal conditions and an approximation to the radial groundwater flow equation. Because the method of Davison (1981) was based on time lag analysis of drawdown response to determine hydraulic diffusivity, the calculated diffusivity is sensitive to the ability to measure small drawdowns or pressure changes. Furthermore, depending upon which approximations to the radial groundwater flow equation are used (i.e., Cooper and Jacob, 1946; Johnson et al., 1966; Van Golft-Racht, 1982), the calculated hydraulic diffusivity may vary by up to a factor of three.

Although Davison (1985) reported hydraulic diffusivities, estimates of specific storage are required to determine hydraulic conductivity from these diffusivities. Recognizing the wide range of specific storages in fractured rocks and the generally unreliable methods for determining them (see Barker and Black, 1983; Black, 1985 and Section 2.2), the hydraulic diffusivities are of limited practical

use in defining reliable measures of hydraulic conductivity. Best estimates of specific storage and therefore hydraulic conductivity from the diffusivity data are likely to be plus or minus an order of magnitude.

3.9.2 Porosity

No porosity measurements for the URL lease area were encountered in the literature reviewed.

3.9.3 Fracture Charcteristics

Stone et al. (1984) summarized the results of surface fracture mapping conducted on the URL lease area. They found that the majority of fractures could be classified as either shallow dipping (less than 30°) or steeply dipping (greater than 60°). These findings are somewhat biased to steeply dipping fractures since relief at the site is generally low and the existence of shallow dipping fractures was best discerned from the relatively small number of vertical cliff faces. Stone et al. (1984) found predominant strike directions for both shallow and steeply dipping fracture groups. In addition, Stone et al. (1984) subdivided a portion of the URL lease area and analyzed the fracture characteristics within these areas. While there is nothing technically wrong with such an approach, there appears to be little physical basis for the selected areal definition. As a result, the conclusions drawn based on comparison of these sub-areas have little apparent meaning.

In addition to strike and dip information, Stone et al. (1984) presented trace length and spacing data for both fracture groups (i.e., steeply and shallow dipping). Both sets of trace length data contain certain censoring and truncation biases, a fact acknowledged by Stone et al. (1984). Steeply dipping fracture lengths may be biased since parts of the fracture may be covered with overburden. Shallow dipping fractures were found to be present at the bottom of rock faces

leading Stone et al. (1984) to assume that the orientation and length of these fractures could be estimated by the slope and length of the soil covered terraces in front of the rock faces. Unfortunately, this conclusion is unsubstantiated and hence the trace length data of the shallow dipping fractures should be regarded as merely bounding values. In spite of these difficulties, Stone et al. (1984) were successful in fitting a log-normal distribution to the trace length data. They reported correlation coefficients of 0.998 and 0.996 - 0.997 for the shallow and steeply dipping fracture zones.

Spacing data for the shallow dipping fracture group was obtained from cliff face data and was found to give a relatively high correlation coefficient ($r = 0.987$) when fit to an exponential distribution. Stone et al. (1984) analyzed the spacing data of the steeply dipping fractures in terms of the sub-areas described earlier. Unfortunately, it was found that neither an exponential nor a log-normal distribution could be used to fit the data. This finding was attributed (at least partially) to the existence of small isolated outcrops that gave rise to truncation of fracture lengths, an explanation which would appear reasonable.

Brown (1982) also summarized the geology and fracture characteristics at the URL site. Unfortunately, his information is too brief and general to allow an evaluation of the quality of data. Certainly, his general findings were similar to those of Stone et al. (1984) discussed above.

3.10 AECL's ATIKOKAN RESEARCH AREA

3.10.1 Permeability

Results of permeability testing at the Atikokan Research Area of AECL were given by Leech (1981), Stone (1981), Gartner Lee Associates Ltd. (1982), Pearson (1982), Lee et al. (1982, 1983) and Pearson et al. (1984). The report by Gartner Lee Associates Ltd. (1982) describing the early hydraulic testing in the Atikokan boreholes was not available from Atomic Energy of Canada Ltd.

Leech (1981) and Lee et al. (1983) described the test equipment, test methods and analytical techniques for the deep borehole testing program completed by Gartner Lee Associates Ltd. for AECL. Single packers and straddle packers with submersible pressure transducers were used in conjunction with tubing strings to complete slug, pressure-pulse and constant-pressure injection tests. The hydraulic conductivity range for each test method as reported by Lee et al. (1983) is appropriate although details of testing, such as methods of measuring low fluid flow rates during injection testing, were not given.

Stone (1981), Leech (1981) and Lee et al. (1983) reported hydraulic conductivities for the Atikokan area from single-borehole tests which ranged from 10^{-14} to 10^{-5} $m \cdot s^{-1}$. Hydraulic conductivities less than 10^{-11} $m \cdot s^{-1}$ were presumably determined from pressure-pulse tests. In order to calculate such hydraulic conductivities, it is necessary to know the test interval compressibility as discussed previously for several other test program (e.g., see sections 3.2.1 and 3.7.1). It is not clear that the equipment used at the Atikokan test site was capable of reliably measuring this compressibility. As the measurement of this compressibility is not described, it is assumed that the compressibility was assumed equal to that of ordinary water. Given

this assumption, we would expect that the pressure-pulse tests would underestimate the hydraulic conductivity of the test interval as observed by Hsieh et al. (1983), Forster and Gale (1981a) and Spane and Thorne (1985). However Lee et al. (1983) compared hydraulic conductivities determined from pressure-pulse tests and injection tests and observed higher hydraulic conductivities from the pressure-pulse tests than from the injection tests by factors up to 7.5. This overestimation of hydraulic conductivity from pressure-pulse tests is inconsistent with the results from other comparable borehole test programs and suggests that the results of either the pressure-pulse tests or the injection tests may be unreliable by up to a factor of 7.5.

An additional source of uncertainty in the test results stems from the uncertain reliability of the formation pressure or hydraulic head data for individual test intervals (Lee et al., 1983). Uncertainty in formation pressure can result in errors in calculated hydraulic conductivity by factors of two to three depending upon the magnitude of the applied test pressure in both pressure-pulse tests and injection tests.

In summary, the hydraulic conductivity data from single-borehole tests reported for the Atikokan area are likely reliable to within a factor of two to three for hydraulic conductivities greater than 10^{-9} $m \cdot s^{-1}$, to within an order of magnitude for hydraulic conductivities between 10^{-12} and 10^{-9} $m \cdot s^{-1}$ and of uncertain reliability for hydraulic conductivities less than 10^{-12} $m \cdot s^{-1}$. The range of reported hydraulic conductivities are, however, consistent with results from other test programs.

Hydraulic conductivity from interference tests at Atikokan was reported by Pearson et al. (1984). An average interborehole hydraulic conductivity of approximately 10^{-8} $m \cdot s^{-1}$ was reported over an inter-borehole distance of several hundred metres.

Although the response data were given by Pearson et al. (1984), the methods for determining the inter-borehole hydraulic conductivity were not. Given that the small (maximum of 0.4 m) drawdown response of the observation interval may be strongly influenced by natural pressure transients and barometric pressure effects, the calculated hydraulic conductivity is likely unreliable.

3.10.2 Porosity

Porosity measurements conducted on core samples from borehole ATK-1 of granodiorite and granite were reported by Drury (1981). These values ranged from .003 to .010 with the majority of measurements being reported between .004 and .006. These values appear typical of other porosity measurements made on cores from the Canadian Shield. However, Drury (1981) provided no information regarding the test technique used to obtain these numbers.

3.10.3 Fracture Characteristics

Stone (1980) reported the results of surface mapping conducted in the Eye Dashawa Pluton near Atikokan, Ontario. More than 9,000 fractures were mapped noting such characteristics as orientation, length, frequency and infilling material. Fracture data were collected over three areal scales termed regional, detailed and grid. The regional area covered the entire pluton area while the detailed area (9 km^2) and grid area (7,000 m^2) were significantly smaller. Orientations for all three areas were presented in terms of polar plots, and were found to be similar. The lack of any significant vertical relief within any of the three areas would suggest a sampling bias should be present within the fracture mapping data, a hypothesis that might be confirmed by the general absence of horizontal/subhorizontal fractures.

Log-normal probability distribution functions were fit to fracture frequency data from both the detailed and regional areas, although no indication of the goodness of this fit is mentioned. Stone (1980) did indicate that the difference between fracture frequency of these two areas is not significant. Fracture frequencies were not recorded in the grid area so comparisons with this area were not possible. Again the bias introduced by surface mapping of nearly horizontal planes should be recognized.

Log-normal distributions were fit to fracture length data of all three mapping areas (grid, detail, regional) although no quantitative information was given regarding the adequacy of these fits. Two sources of error were present with the fracture length data and were acknowledged by Stone (1980). These included the unavoidable censoring of fracture lengths that are larger than the outcrop, as well as the truncation bias introduced by the sampling procedure (i.e., failure to log fractures that were less than 0.5 m in length).

Brown et al. (1980) presented preliminary fracture orientation data based on aerial photo interpretation and regional ground surface mapping. Most of their findings were presented in terms of average (or dominant) fracture directions. Their results compared favourably to those of Stone (1981), although the concerns regarding undersampling of horizontal or subhorizonal features also apply.

Hillary (1982a,b) presented limited fracture characteristic data for boreholes ATK-1 to ATK-5 drilled at the Atikokan Research Area. The majority of this information pertains to fracture orientation (i.e., strike and dip). Hillary (1982a,b) indicated that a gyroscopic survey was used to correct for borehole orientation, so borehole deviation should not be a concern. Hillary's (1982a,b) shallow fracture orientation data also compared favourably to the dominant sets determined by Stone (1980).

3.11 AECL's CHALK RIVER RESEARCH AREA

3.11.1 Permeability

Field permeability data for the Chalk River Research Area of AECL were reported by Raven (1980), Davison (1981), Raven (1982), Raven and Smedley (1983), Raven et al. (1984b, 1985a), Raven and Novakowski (1984) and Raven (1986). Laboratory permeability data were given by Cooley and Butters (1979). The most comprehensive reporting of permeability was given by Raven (1986) from drilling and testing in a suite of 17 shallow boreholes.

Raven (1980) described the first permeability data obtained at the Chalk River site from the results of single-packer drill stem tests, and straddle-packer injection tests. The permeability data were determined from pressure-pulse tests and constant-pressure injection tests. Low flow rate measurement capability was stated by Raven (1980) as 0.18 $mL \cdot min^{-1}$ although Raven (1980) further stated that flow rates at or below 0.60 $mL \cdot min^{-1}$ without surface and downhole temperature measurement (downhole temperature measurement was not part of the 1977-78 test equipment) were suspect. Raven (1980) did not calculate hydraulic conductivities from most of the injection test data, but presented the test data as flow rate per unit injection heads ($Q/\Delta H$). These data ranged from 10^{-7} $m^2 \cdot s^{-1}$ to 10^{-3} $m^2 \cdot s^{-1}$ and appear reasonable and consistent with similar data from other test programs.

Raven (1980) also presented permeability data determined from Wang et al. (1977) early-time analysis of pressure-pulse tests. The data presented by Raven (1980) were likely unreliable as a result of air leakage, uncertain thermal transients and unknown test interval compressibilities (Raven, 1980). This data is at best accurate to within plus or minus an order of magnitude.

Davison (1981) presented permeability data determined from single-borehole, single-packer and straddle-packer tests and straddle-packer hydraulic interference tests. Equivalent single fracture apertures were determined from pressure-pulse tests using a modified form of the early-time equation. Although Davison stated that test interval compressibilities as a result of entrapped air in the packer mandrel were considered in the test analysis, the method is not immediately clear. Davison (1981) also compared injection test results with pressure-pulse test results and found a favourable comparison. Repeated testing of borehole intervals over a several month period, also showed that the hydraulic conductivity was variable to within a factor of two. Given the lack of description of the test methods, it is uncertain whether this variability of hydraulic conductivity is real or the result of inaccuracies in measurement. Davison also noted that the minimum reliable flow rate measurement for injection tests was 0.3 $mL \cdot min^{-1}$. This translates to a minimum equivalent single fracture aperture of 5 m. The reported ranges of hydraulic conductivity from injection tests (2×10^{-11} to 8×10^{-6} $m \cdot s^{-1}$) appear consistent with this flow rate measurement capability.

Davison (1981) also reported the results of several hydraulic interference tests completed between boreholes CR-6 and CR-7 using straddle packers. The test results were analyzed using the time lag method of Johnson et al. (1966) with observation interval storage corrections from Prats and Scott (1975). As indicated in Section 3.9.1, the calculated hydraulic diffusivity can vary by factors up to three depending upon the approximation to the radial flow equation and resolution capability for early time pressure response. In comparing the calculated hydraulic diffusivities to those predicted using single-borehole measures of transmissivity and storage determined for a rigid parallel plate model, Davison observed that calculated diffusivities were less than the predicted diffusivities. This result is to be expected as natural fractures are deformable and the predicted

diffusivity would be too high as a result of underestimation of fracture storativity. This comparison shows that the assumptions of a rigid parallel plate model are inappropriate for analysis of interference test data to determine hydraulic conductivities from hydraulic diffusivities. Consequently, Davison's hydraulic diffusivity data can not be used to determine hydraulic conductivity without reliable specific storages.

Raven (1986) described the test methods, results and analytical methods of straddle-packer injection tests and hydraulic interference tests to measure the hydraulic properties of a 200 m x 150 m by 50 m deep rock block at Chalk River. Hydraulic conductivities from straddle-packer injection tests reported by Raven (1986) ranged from 10^{-11} to 10^{-4} $m \cdot s^{-1}$. The measurement limits for flow rate (0.02 $mL \cdot min^{-1}$ to 6 $L \cdot min^{-1}$) are consistent with the reported range of hydraulic conductivity for the 1.5 to 2.0 m length test intervals. However, the lower flow rates are suspect and therefore the hydraulic conductivities below 10^{-10} $m \cdot s^{-1}$ are likely only reliable to within an order of magnitude. Hydraulic conductivities from single-borehole tests above 10^{-10} $m \cdot s^{-1}$ are reliable to within a factor of two. Hydraulic conductivities were determined using the steady-state assumption and Hvorslev's (1951) shape constant.

Raven (1986) also presented the results of hydraulic interference tests analyzed using conventional Theis methods. The calculated transmissivities for selected fracture zones were expressed as equivalent single fracture apertures and compared to single-borehole injection test results. The comparison was generally not favourable and suggested that the fracture zones are highly heterogeneous. Several pumping tests were further analyzed using the uniform-flux, single, horizontal fracture model of Gringarten and Ramey (1974). The calculated radial and vertical hydraulic conductivities also did not compare favourably with the results of the straddle-packer injection

tests. Vertical hydraulic diffusivities were also reported by Raven (1986) using pump tests of fracture zone No. 1 and the ratio method of Neuman and Witherspoon (1972). The diffusivities ranged from 2×10^{-5} to 4×10^{-2} $m^2 \cdot s^{-1}$. Using reasonable specific storages of 10^{-6} to 10^{-4}, the hydraulic conductivities calculated from the diffusivities were similar to hydraulic conductivities determined from straddle-packer injection tests.

The reliability of the hydraulic conductivities determined from the straddle-packer tests were evaluated by validation of a two-dimensional numerical model of groundwater flow at the site to field measurements of hydraulic head (Raven et al., 1985a). This modeling exercise suggested that the field measurements of hydraulic conductivity were representative of in situ conditions to depths of 30 m but overestimated hydraulic conductivity below 30 m depth by factors of 100 to 1000.

Raven (1986) also reported integration of fracture orientation and injection test data to estimate anisotropic hydraulic conductivities. Because of the simple methods used (Snow, 1965) and the failure to consider the effects of finite fracture extent, the anisotropic hydraulic conductivities calculated are probably unreliable.

Cooley and Butters (1979) described permeability measurements completed on intact samples of core from boreholes CR-6 and CR-7 using the pressure pulse technique (Brace et al., 1968). The calculated hydraulic conductivities ranged from less than 5×10^{-13} $m \cdot s^{-1}$ to 8×10^{-12} $m \cdot s^{-1}$ at ambient and representative in situ effective stresses. The hydraulic conductivities are reliable and comparable to other test program results.

3.11.2 Porosity

A number of individuals have measured the porosity of crystalline rock samples from the Chalk River Research Area including Drury (1981), Wadden (1979) and Radwan (1979). Drury's (1981) values were obtained from cores of gneiss taken from boreholes CR-1, CR-6, CR-7, CR-8 and CR-9 and ranged from .001 to .026. As with the values reported by Drury (1981) for the Atikokan Research Areas, these values are comparable to values reported by other researchers. Drury (1981) did not identify the method employed.

Wadden (1979) also estimated the porosity of cores from boreholes CR-6 and CR-7. He used a water immersion technique and performed duplicate measurements on sections of the same core in an effort to establish the precision of the technique. Based on the results of these measurements, he concluded that his technique was precise to $\pm$ .0003. The porosity values ranged from 9.7×10^{-4} to 4.8×10^{-2} for cores from CR-6 although the vast majority of values were in the range of 2×10^{-3} to 3×10^{-3}. The upper bound on measured values was anomalously high and resulted from a single measured value. No reason for the existence of such a high value was suggested and with the exception of this value, the remainder of the measurements on CR-6 cores appear reasonable. Wadden's (1979) measurements on CR-7 cores also appear to be reliable, ranging from 7.4×10^{-4} to 3.2×10^{-3}.

Radwan (1979) used the same technique as Wadden (1979) to obtain porosity measurements on core samples from borehole CR-8. His values ranged from 1.8×10^{-3} to 3.7×10^{-3} and would generally appear to be reliable.

3.11.3 Fracture Characteristics

Raven (1980) presented some of the earliest fracture information on the Chalk River Research Area. His information consisted primarily of surface fracture maps, air photo analysis and

some preliminary downhole information. Raven (1980) presented polar plots and frequency histograms for both the total study area as well as a number of sub-areas. Raven (1980) acknowledged the existence of a number of biases in his data, including:

- line sampling biases (uncorrected only in histogram plots);
- poor representation of horizontal to sub-horizontal fractures;
- truncation bias (introduced by failure to map fracture lengths smaller than 1.0 m);
- censoring bias on fracture trace length.

Raven (1980) concluded that fractures within the Chalk River study area are highly dispersed in orientation and show the presence of locally persistent fracture sets. Raven also presented mean fracture spacing and length for each of the three sub-areas under consideration.

Raven (1980) also attempted to compare the results of the surface fracture mapping with air photo analyses. Although the data from these two analyses are (as Raven acknowledged) from significantly different scales, two of the major fracture sets could be identified in both sets of data.

Raven (1986) described the results of surface fracture mapping and borehole fracture logging carried out at the flow system study area. Fracture orientation data were corrected for sampling orientation bias using the method of Terzaghi (1965) and were presented in the form of lower hemisphere equal-area projections. Raven (1986) reported borehole fracture orientation data from two different sources - acoustic televiewer and borehole television surveys. Polar plots obtained from both borehole fracture mapping methods indicated the existence of the same fracture sets, giving a general indication of the reliability of the methods.

3.12 AECL's WHITESHELL RESEARCH AREA

3.12.1 Permeability

Davison (1980, 1981) and Cooley and Butters (1979) reported permeability data for the Whiteshell Research Area of AECL. The methods, test equipment and analytical techniques for these field and laboratory tests were similar to those reported by the same authors for the Chalk River Research Area and need not be discussed in detail. However, several observations are relevant to assessing the reliability of the reported hydraulic conductivities.

Davison (1980, 1981) reported hydraulic conductivities determined from single-packer, drill stem, pressure-pulse tests and straddle-packer injection tests. The hydraulic conductivities reported by Davison ranged from 2×10^{-13} $m \cdot s^{-1}$ to 5×10^{-7} $m \cdot s^{-1}$. The flow rate measurement range was given (Davison, 1980) as 0.001 $mL \cdot min^{-1}$ to 1.0 $L \cdot min^{-1}$. Although the hydraulic conductivities are consistent with the reported flow rate measurement capability, the low flow rate measurement capability is likely not reliable and therefore the hydraulic conductivities determined from flow rates below 0.1 $mL \cdot min^{-1}$ (i.e., less than 10^{-11} $m \cdot s^{-1}$) are equally unreliable. This is particularly true for tests described by Davison (1980) where downhole temperature measurement was not performed.

Davison (1980) also reported hydraulic conductivities determined from pressure-pulse tests using the Wang et al. (1977) early time analysis. As indicated for the Chalk River data, uncertainty in test interval compressibility, thermal transients and air leakage likely introduced significant uncertainty of plus or minus an order of magnitude in the reliability of these calculated hydraulic conductivities. The results of repeated pressure-pulse testing on several test intervals are consistent with this reliability

estimation, as Davison (1980) reported that the hydraulic conductivities varied by plus or minus one order of magnitude.

In summary, the field hydraulic conductivities reported by Davison (1980, 1981) are likely accurate to within an order of magnitude for hydraulic conductivities below 10^{-11} $m \cdot s^{-1}$ and to within a factor of two for hydraulic conductivities above 10^{-11} $m \cdot s^{-1}$. The hydraulic conductivities determined by Cooley and Butters (1979) from core samples using the pressure-pulse method (Brace et al., 1968) ranged from 6×10^{-13} $m \cdot s^{-1}$ to 3×10^{-11} $m \cdot s^{-1}$ for ambient and representative in situ effective stresses. These results are reliable and comparable to data from other test programs.

3.12.2 Porosity

A number of researchers have conducted porosity measurements on samples from the Whiteshell Research Area including Wadden (1979), Radwan (1979), Drury (1981) and Chernis (1981, 1983, 1984). Two of these investigators, Wadden (1979) and Radwan (1979) used a water immersion technique to obtain their estimates. Wadden (1979) reported a precision of $\pm$ .0003 based on repetitive measurements performed on sections of the same core. His values ranged from 2.9×10^{-3} to 4.0×10^{-3} for cores from WN-1 and from 1.6×10^{-3} to 2.8×10^{-3} for cores from WN-2. Radwan (1979) reported values ranging from 2.7×10^{-3} to 6.0×10^{-3} for cores from WN-4. Both of these sets of measurements would appear to be reliable based on their consistency with other reported values.

Drury (1981) reported the results of porosity measurements obtained using an unspecified technique on core samples from boreholes WN-1, WN-2 and WN-4. His values ranged from 1×10^{-3} to 3×10^{-3} for borehole WN-1, from 2×10^{-3} to 3×10^{-3} for borehole WN-2 and from 2×10^{-3} to 1.1×10^{-2} for borehole

WN-4. Again, although no information was presented on measurement technique or procedure, these values compare favourably to other reported values and for this reason were judged reliable.

Chernis (1983, 1984) used a scanning electron microscope (SEM) to obtain estimates of the porosity of samples of granite and metatonalite. His procedure involved preparing polished thin sections, approximately 60 m in thickness, running parallel traverses across the specimen and recording the imagery on videocassettes. Subsequently, an estimate of the porosity was obtained by summing the total crack lengths along the traverse as a percentage of the total traverse length. Although a number of potential problems could influence these measurements, such as the existence of extremely small test specimens biasing the sample of fractures, or the potential for significant stress relief effects, the values reported by Chernis (1983, 1984) for granite appear reasonable. Granite total porosity values of 0.24% (Chernis, 1983) and 0.23% and 0.28% (Chernis, 1984) were reported for granite specimens while a value of only 0.06% was reported for metatonalite (Chernis, 1983).

3.12.3 Fracture Characteristics

The Whiteshell Research Area has very poor exposure of bedrock and as such, all fracture related information pertains to subsurface (borehole) investigations. This information includes fracture densities determined from core logs of boreholes WN-1 and WN-2, orientation information from core logs, borehole television and acoustic televiewer logs. Davison (1980) indicated that a poor correlation existed between the orientation data obtained from core logs and that obtained from the borehole television logs, and suggested that erratic magnetic interference may have affected the television camera compass. No comparison to the acoustic televiewer orientation data was made allowing this hypothesis to remain unsubstantiated. As a result, both the core log and borehole television orientation data should be regarded as unreliable.

3.13 MISCELLANEOUS SITES

3.13.1 Permeability

Permeability data were also reported for the following sites and research programs:

- PAGIS (Performance Assessment of Geological Isolation Systems) Sites at Auriat and Barfleur, France;
- AECL's Research Area 7 - East Bull Lake;
- Geothermal Research Program at Rosemanowes Quarry by Camborne School of Mines;
- Geothermal Research Program at Fenton Hill, New Mexico by Los Almos National Laboratories;
- Exploration Program for a feasibility study for a pumped hydroelectric energy storage program (the Illinois Deep Hole Project);
- Miscellaneous National Nuclear Waste Isolation Programs inlcuding those of Switzerland, South Africa, India, and Norway;
- Research being conducted by researchers associated with various academic institutions (e.g., Evans, 1983; Snow, 1979);
- Data collected by commerical and industrial corporations (e.g., hydroelectric, mining companies).

In general, the permeabilities or hydraulic conductivities reported by the above programs have similar reliability as those from the large programs previously described. Typically this means that hydraulic conductivities less than 10^{-10} $m \cdot s^{-1}$ have reliability of approximately one order of magnitude, (the reliability decreasing with hydraulic conductivity) whereas hydraulic conductivities greater than 10^{-10} $m \cdot s^{-1}$ are likely accurate to within a factor of two to three. Specific programs are only

discussed in this section if sufficient details of test equipment, methodology and analytical technique were provided. Lack of detailed discussion on the representativeness and reliability of permeability data in this section for specific programs listed above implies insufficient information.

Permeability data for the East Bull Research Area of AECL were reported by Raven et al. (1984a, 1985b, 1986) from the results of single-packer and straddle-packer pump tests, slug tests and injection tests. The most comprehensive reporting of hydraulic conductivity was provided by Raven et al. (1986) from testing in both shallow (less than 100 m depth) and deep boreholes (to 800 m depth). Single-packer and straddle-packer slug tests were conducted in the shallow boreholes and a distribution of hydraulic conductivities were tabulated and compared with the results of injection tests completed at the Chalk River Research Area (Figure 3.14). Because packer leakage or bypass was noted in many of the tests completed in the shallow air percussion-drilled boreholes at East Bull Lake, the hydraulic conductivities may be overestimated by an uncertain amount. Comparison of the distributions of hydraulic conductivities (Figure 3.14) suggests such an overestimation, although the difference in hydraulic conductivities may also result from different lithologic and tectonic settings of the two sites. However, the sum of the transmissivities determined from individual packer tests and open borehole tests were comparable to within a factor of two to three, suggesting that the hydraulic conductivities have similar reliability.

Raven et al. (1984a, 1986) also reported hydraulic conductivities from deep borehole testing determined from pump, injection and slug tests. For the 50 - 100 m length test intervals the hydraulic conductivity generally decreased from 10^{-8} to 10^{-11} $m \cdot s^{-1}$ with depth. The reliability of these numbers was evaluated through repeat testing. This repeat testing (Figure 3.15) showed that the first profile of hydraulic conductivity for deep boreholes EBL-1 and EBL-2 determined from short-term slug and injection tests generally

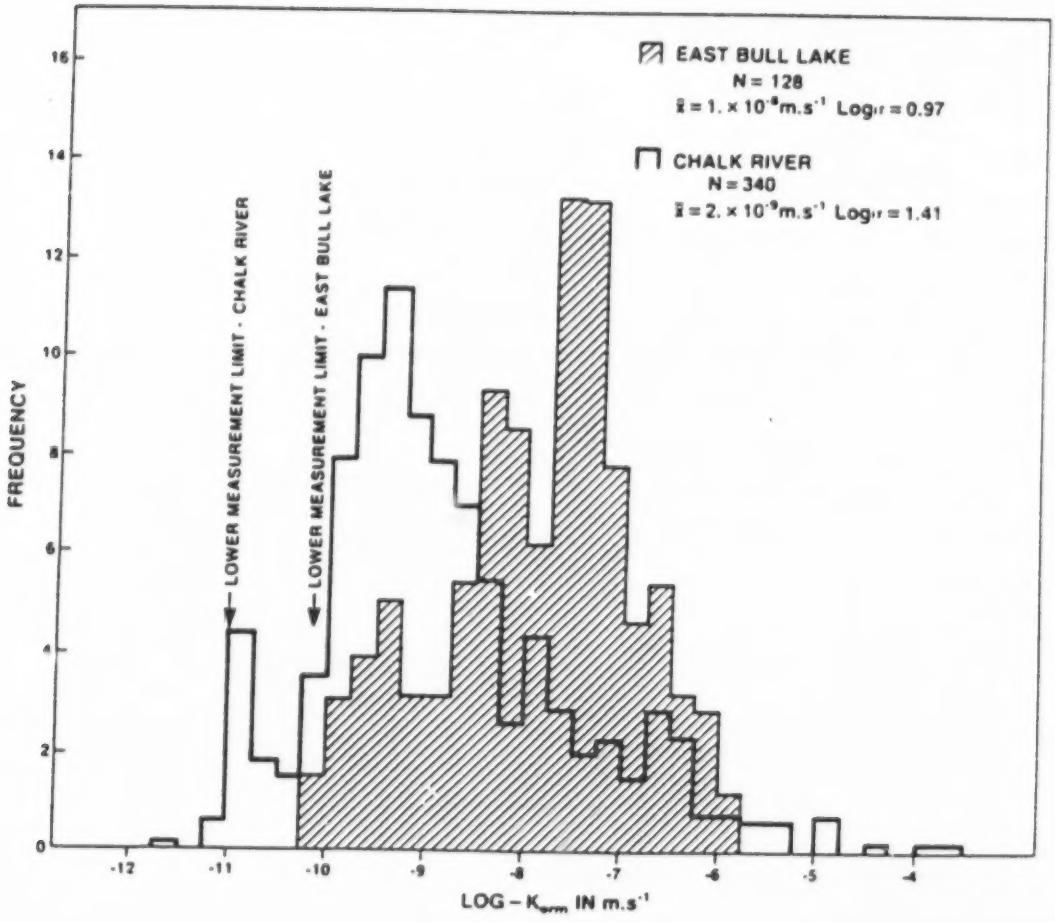


Figure 3.14 Histogram of the distribution of the common logarithm of equivalent rock mass hydraulic conductivity, K_{erm}, determined from packer tests completed from 0 to 75 m depth at the East Bull Lake and Chalk River research areas (after Raven et al., 1986)

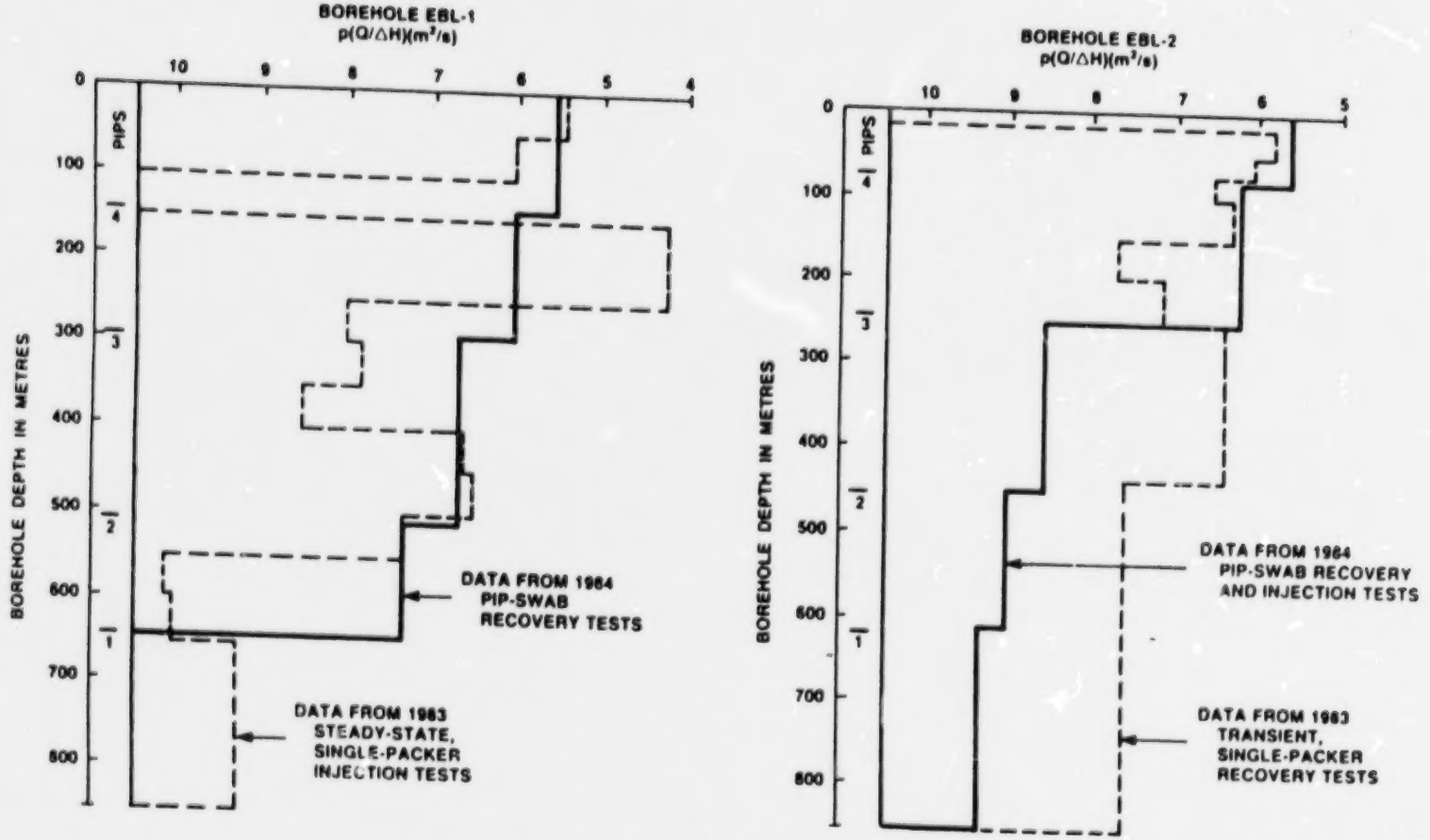


Figure 3.15 Flow rate per unit head (Q/ΔH) profiles for boreholes EBL-1 and EBL-2 determined from 1983 packer tests and 1984 PIP tests. The test data are plotted as the negative common logarithm (p) of Q/ΔH expressed as m^2/s (after Davison et al., 1986)

INTERA

overestimated hydraulic conductivity by greater than one order of magnitude particularly for deep sections of borehole EBL-2.

Raven et al. (1984a) also reported comparison of equivalent single fracture apertures determined from constant-pressure injection tests and pressure-pulse tests. The pressure-pulse apertures were generally less than the injection test apertures by factors of two to three. As the pressure-pulse tests were analyzed using known test interval compressibilities, it may be that the injection tests which were conducted through 800 m of injection tubing were less reliable than the pressure-pulse tests.

As a result of repeated testing, (i.e., from straddle-packer tests, production-injection packer tests and casing-packer tests) the hydraulic conductivity of the East Bull Lake Research Area is likely reliable to within a factor of three.

Pine (1983) described the equipment method and results of constant-pressure injection tests, slug tests and pump tests performed by the Camborne School of Mines in the Carnmenellis Granite at depths of 1500 - 2000 m. The reported permeabilities (hydraulic conductivities) for low pressure tests ranged from 0.2 to 10 μ darcies (2×10^{-12} to 1×10^{-10} $m \cdot s^{-1}$). The variation between different tests on the same interval and therefore data reliability was about one order of magnitude. These hydraulic conductivities are also consistent with results from other test programs.

Potter (1978) provided permeability data from laboratory pressure-pulse testing of intact core samples of granite from the Fenton Hill Hot Dry Rock site. Permeabilities were determined using the Brace et al. (1968) analysis technique for various confining pressures and temperatures. The permeabilities (hydraulic conductivities) ranged from 0.001 to 10 μ darcies (10^{-14} to 10^{-10} $m \cdot s^{-1}$). The experimental methods described by

Potter (1978) were well documented and controlled with the reliability of the reported permeabilities expected to be within a factor of two. The extent to which the results are representative of in situ conditions is less certain as a consequence of stress relief during drilling and uncertain in situ stress conditions. Certainly the results are consistent with permeabilities reported for intact granite from other programs.

Haimson and Doe (1983) described an interesting series of single-packer injection and pressure-pulse tests performed to depths of 1600 m in granite as part of the Illinois Deep Hole Project. Haimson and Doe provided a good description of test equipment, procedures and analytical methods which allowed an assessment of the reliability of the test results. Haimson and Doe analyzed the injection tests using the steady-state assumption and the shape factor of Hvorslev (1951) and the pressure-pulse tests using the type-curve method of Bredehoeft and Papadopulos (1980) and the early-time decay method of Wang et al. (1977). Haimson and Doe identified sources of uncertainty in calculated hydraulic conductivity from the injection tests as the radius of test influence ($\pm$ 20% error in conductivity) and from the pressure-pulse tests as the selection of the appropriate type curve (error factor of 2.2 in conductivity). While these uncertainty estimates are in themselves appropriate, Doe and Haimson neglected the most significant source of uncertainty in the pressure-pulse tests. Both of the analytical methods for the determination of hydraulic conductivity from pressure-pulse tests assumed a test interval compressibility that resulted only from the compressibility of water. As has been demonstrated in other test programs, the actual test interval compressibilities may be up to two orders of magnitude greater than that attributable solely to water compressibility as a result of non-rigid borehole equipment. This error may introduce up to two orders of magnitude underestimation of hydraulic conductivity. Haimson and Doe observed such a discrepancy between the injection test results

and the pressure-pulse test results but did not provide an explanation for the discrepancy. This suggests that only the injection test data of Haimson and Doe are reliable to within a factor of two to three and that the hydraulic conductivity decrease with depth discussed by these authors is not as great, decreasing not to 10^{-12} $m \cdot s^{-1}$ as inferred from the pulse tests but only to 10^{-10} $m \cdot s^{-1}$ as indicated by the injection tests.

Results of permeability testing in a deep borehole in Switzerland were given by Pickens et al. (1985). Permeabilities were estimated using single packers and straddle packers and slug, pulse and drill stem tests as well as long-term pressure recovery monitoring. The hydraulic conductivities for the Bottstein borehole were reported to vary between 10^{-14} and 10^{-10} $m \cdot s^{-1}$ with generally lower hydraulic conductivity resulting from analysis of the long-term monitoring. The comparison of hydraulic conductivities from different test methods and analytical techniques showed that the hydraulic conductivities were only accurate to within an order of magnitude (Pickens et al., 1985). Hydraulic conductivity in the range of 10^{-14} to 10^{-10} $m \cdot s^{-1}$ determined from conventional analysis of pulse and drill stem tests are expected to be slightly less reliable as a consequence of the effects of borehole pressure history and thermal expansion/contraction of fluid. Although recent numerical techniques (Pickens et al., 1986) allow for consideration of these effects in analysis of hydraulic tests, many of the tests completed as part of the Swiss program did not have reliable temperature measurement capability within the test interval.

3.13.2 Porosity

Norton and Knapp (1977) determined total porosities on approximately 70 different samples of crystalline rock from a variety of sites, predominately in the American Mid-west. These values were determined by calculating the bulk rock density through immersion techniques and the grain density established on a finely ground sample. Norton and Knapp (1977) indicated that for the lower porosity rocks examined in their study (e.g., less than 0.05) their technique should be accurate to within 2 per cent of the total porosity. Isotropic metamorphic rocks were found to have a total porosity of between 1×10^{-2} and 3×10^{-2} whereas anisotropic rocks were found to range from 1×10^{-2} to 1×10^{-1}. It is difficult to ascertain the reliability of the porosities reported by Norton and Knapp (1977). Certainly, the porosities appear to be significantly higher than values for similar rocks reported elsewhere. This may be a reflection of the fact that their samples consisted largely of rocks which had been subjected to various geologic and geochemical altering mechanisms.

Evans (1983) described in detail how he obtained two sets of porosity measurements using a mercury porosimeter and a grain density technique. The majority of the samples analyzed yielded a higher total porosity from the grain density technique than from the mercury porosimeter measurements. This, as Evans (1983) pointed out, should be expected, since the mercury porosimeter is incapable of measuring either pores that are less than 10^{-4} mm or pores that are not interconnected. However there are two major inconsistencies that exist with this hypothesis. One is the existence of a significant portion of the samples (roughly one-third) in which the porosity as determined by the mercury porosimeter was higher than that determined by grain density techniques. The other problem is associated with the magnitude of the difference between the two sets of measurements. Since the samples were all granodiorite and originated from the same mine, it seems unlikely that a systematic error of the type suggested by Evans (1983) would produce errors of widely varying magnitude.

3.13.3 Fracture Characteristics

Fracture information for AECL's East Bull Lake Research area is relatively limited. Information presented by Raven et al. (1984a) included major lineament orientation as determined by air photo analysis and subsurface fracture density data determined from borehole television camera surveys. Although there is nothing to suggest that the information is unreliable, it must be recognized that this information is preliminary and as such does not provide a complete description of the fracture characteristics of the site.

The information provided by Pine and Batchelor (1984) describing the fracture characteristics of the Carnmenellis Granite at the Camborne School of Mines is also somewhat limited. Although orientations and spacings were presented for the major fracture sets, no information is provided as to how these data were obtained, rendering a judgement of its quality difficult.

Haimson and Doe (1983) described in detail the methodology used to determine subsurface fracture orientations at the site of the Illinois Deep Hole Project. Their method involved the use of a downhole television camera to orient sections of the core. Although Haimson and Doe (1983) indicated that major fracture orientations compare favourably with those of shallower holes, the relatively small percentage of fractures that were capable of being oriented by the television camera together with the relatively large number of core fractures would tend to cast some doubt on the representativeness of their data.

4. SUMMARY AND CONCLUSIONS

4.1 PERMEABILITY

The large data base of permeability (hydraulic conductivity) for crystalline rocks has been critically reviewed in this report. The majority of permeability values were determined from borehole tests using three test methods: injection tests, transient pressure-pulse tests and constant-discharge transient well tests. The similarity of equipment, procedures and analytical methods for these tests allows for comparison of test results, testing limits and data representativeness between individual investigation programs. For many of the larger programs, detailed descriptions of test equipment and test procedures facilitated evaluation of the suitability of the test used to collect the data and therefore the reliability of the data. Different testing methods performed in the same rock mass (e.g., the Stripa Mine, Sweden) have also been used to determine data reliability and representativeness.

The vast majority of permeability data cited in the studies reviewed in this report, are from single-packer and straddle-packer injection tests analyzed using the steady-state assumption. Evaluation of these test results show that most of the hydraulic conductivity data above 10^{-9} $m \cdot s^{-1}$ are reliable to within a factor of two to three. The uncertainty associated with these higher hydraulic conductivities results from unknown flow field geometry and nonsteady-state conditions.

Many of the injection test programs reviewed during this study indicate lower measurement limits for hydraulic conductivity of 10^{-11} to 10^{-12} $m \cdot s^{-1}$. At these low levels, the calculated hydraulic conductivity may at best only be accurate to within an order of magnitude. The accuracy of hydraulic conductivity

measurements from injection tests is a function of the accuracy of the flow rate and injection head measurements. Below 10^{-9} $m \cdot s^{-1}$ hydraulic conductivity, test results are more strongly influenced by borehole pressure history effects, packer squeeze and creep, packer leakage and thermal effects.

Many of the radioactive waste disposal programs have attempted to use transient pressure-pulse tests to obtain more reliable measures of hydraulic conductivity in the range of 10^{-9} to 10^{-14} $m \cdot s^{-1}$. The transient pressure-pulse test is theoretically and practically capable of reliably determining hydraulic conductivities in this range within a factor of two to three. However, many of the early attempts to use this test method were unsuccessful, principally as a result of failure to consider borehole history effects, thermal effects, packer squeeze and leakage and most importantly, packer compressibility. Many of the transient pressure-pulse tests reported in the literature reviewed as part of this study were incorrectly analyzed using an erroneous estimate of test interval compressibility. This error resulted in underestimation of hydraulic conductivity by up to two orders of magnitude. Use of a more accurate test interval compressibility resolves many of the inconsistencies observed in early test programs where hydraulic conductivities were determined from transient pressure-pulse tests and injection tests (i.e., Forster and Gale, 1981b; Hsieh et al., 1983; Haimson and Doe, 1983; Spane and Thorne, 1985). Because of uncertainty in borehole pressure history effects, packer squeeze, packer leakage and thermal effects, the reliability of most transient pressure-pulse tests is likely within a factor of three for hydraulic conductivity above 10^{-12} and an order of magnitude for hydraulic conductivities betwewen 10^{-14} and 10^{-12} $m \cdot s^{-1}$.

The most reliable permeability data were from test programs where different test methods were used at different scales and the test procedures, test equipment and analytical methods were well described. In this regard, the permeability data for the Stripa Mine, Sweden is acknowledged as the most reliable data reviewed in this study for the purposes of radioactive waste disposal performance assessment. Well-described test equipment methods and analytical techniques, in conjunction with favourable comparison of hydraulic conductivities from single-borehole tests and two large-scale permeability tests, resulted in a reliable determination of bulk rock mass hydraulic conductivity of about 10^{-10} $m \cdot s^{-1}$.

Although individual programs reviewed as part of this study, have particular short comings and therefore less reliable test results as a consequence of poor test procedures or analytical methods, some general observations can be made on the overall reliability of the permeability data. Hydraulic conductivities above 10^{-9} $m \cdot s^{-1}$ are generally reliable to within a factor of two to three. The reliability of permeability data also decreases with permeability, such that hydraulic conductivities in the range of 10^{-14} to 10^{-10} $m \cdot s^{-1}$ are generally only reliable to within an order of magnitude.

4.2 SPECIFIC STORAGE

Specific storage values cannot be reliably determined from curve fitting of hydraulic test data due to the similarity of the type curves for a wide range (several orders of magnitude) of specific storage values. As a result, most specific storage values are more reliably estimated from component values. The components include fluid compressibility and density and medium compressibility and porosity. Of these, fluid property data are generally well known and as a result most of the uncertainty associated with specific storage estimates

(obtained in this manner) are associated with media properties. The vast majority of rock compressibility data available in the literature were obtained by performing uniaxial and triaxial compression tests on intact cores primarily for the purpose of rock mechanics analysis. Although the range of data reported for such tests is relatively small, there exists considerable uncertainty as to how such data relates to the large scale bulk compressibility required for specific storage estimates of fractured rock.

A limited number of researchers (e.g., Gale, 1977; Carlsson and Olsson, 1982) have attempted to measure in situ rock compressibility, although none have successfully managed to correlate their data to specific storage values obtained from hydraulic tests.

The evaluation of rock compressibility for inclusion in specific storage estimates should be regarded as an area requiring additional research. Rock compressibility in specific storage estimates should currently be regarded as a major source of uncertainty. Total porosity estimates, on the other hand, demonstrate a relatively narrow range (for plutonic rocks) and as a result, the uncertainty associated with such values is relatively small. Although total porosity is comprised of both matrix and fracture components, in crystalline rocks the matrix contribution is by far the dominant one. Fracture porosity may be significant (from a flow standpoint) at very early times in a transient system whereas matrix porosity will predominate at later times. The majority of the porosity values reported in the literature represent matrix values. The narrow range of reported values would indicate that the majority of total porosity measurements reported in the literature would have to be judged as good or acceptable, a notable exception being the anomously high values of Jones et al. (1985).

4.3 FRACTURE CHARACTERISTICS

Fracture characteristic information is subject to a number of errors that may affect the representativeness of the data collected. Surface fracture maps are biased by the orientation of both the mapping surface and the sampling (reference) line. Corrections can be made for sampling line bias although the need for vertical faces may make it difficult to correct for the vertical fracture bias caused by the usually horizontal nature of most outcrops. Trace length data may be biased by lower end truncation caused by setting a minimum fracture length for mapping and by censoring caused by the limited areal extent of the outcrop or mapping surface. Fracture density/spacing may also be affected by this latter variable. In addition to these sampling errors, fracture data are also subject to measurement errors (e.g., length, angle measurements).

To a large extent the significance or severity of these errors will be determined by the eventual use of the fracture data. If the purpose of the data is merely to provide a qualitative indication of the state of the rock mass then the ramifications associated with such errors may not be significant. If, however, the purpose of the fracture data collection program is to provide a representative sample for a statistically based analysis, then the impact of such errors will be more severe. Since the majority of the data reviewed in this study were collected for qualitative purposes, the data are deemed acceptable. A possible exception might be the trace length data reported by Stone et al. (1984) for the URL lease area who used soil covered terrance lengths to estimate his values. Another set of potentially unreliable borehole fracture data are those of Davison (1980) for WNRE. Data from core logs showed only poor correlation to data from borehole television surveys.

REFERENCES

Ahagan, H., 1983. Instruments for hydrogeological and geochemical measurements in deep boreholes, Proc. Int. Symp. on Field Measurements in Geomechanics, Zurich, Switzerland, September 5-8, pp. 1289-1297.

Ahlbom, K., L. Carlsson, S-E Carsten, O. Duran, N-A Larsson, O. Olsson, 1983a. Evaluation of the geological, geophysical and hydrogeological conditions at Fjallveden, KBS TR-83-52, Stockholm, Sweden.

Ahlbom, K., B. Albino, L. Carlsson, G. Nilsson, O. Olsson, L. Stenberg, H. Timje, 1983b. Evaluation of the geological, geophysical and hydrogeological conditions at Gidea, KBS TR-83-53, Stockholm, Sweden.

Ahlbom, K., B. Albino, L. Carlsson, J. Danielssohn, G. Nilsson, O. Olsson, S. Sehlstedt, V. Stejskal, L. Stenberg, 1983c. Evaluation of the geological, geophysical and hydrogeological conditions at Kamlunge, KBS TR-83-54, Stockholm, Sweden.

Ahlbom, K., L. Carlsson, B. Gentzschein, A. Jamtlid, O. Olsson, S. Tiren, 1983d. Evaluation of the geological, geophysical and hydrogeological conditions at Svartboberget, KBS TR-83-55, Stockholm, Sweden.

Almen, K.E., L. Carlsson and K. Hansson, 1981. Some experiences from well testing in precambrian rocks of Sweden. 3rd Proceedings - Invitational Well-Testing Symposium, Well-Testing in Low Permeability Environments (March 26-28, 1980, Berkeley, CA). CONF-800344, LBL-12076, T.W. Doe and W.J. Schwarz, eds., Earth Sciences Division, University of California, Lawrence Berkeley Laboratory, Berkeley, CA, pp. 15-37.

Almen, K., K. Hanson, B-E. Johansson, G. Nilson, O. Anderson, P. Wikberg and H. Ahagen, 1983. Final Disposal of Spent Nuclear Fuel - Equipment for Site Characterization, KBS-83-44, Stockholm, Sweden.

Almen, K.E. and O. Persson, 1984. Determination of Hydraulic Conductivity in Lavia Borehole, Finland, Report YJT-84-20, Nuclear Waste Commission of Finnish Power Companies, Helsinki, Finland.

Andrews, J.N., I.S. Giles, R.L.F. Kay, D.J. Lee, J.K Osmond, J.B. Cowart, P. Fritz, J.F. Barker and J. Gale, 1982. Radioelements, radiogenic helium and age relationships for groundwaters from the granites at Stripa, Sweden, Geochimica et Cosmochimica Acta, 46, pp. 1533-1543.

Autilla, P. 1986. Loviisa Power Station, Final Disposal of Reactor Waste, Geological and Hydrogeological Conditions of the Island of Hastholmen, Report YJT - 86-05 Nuclear Waste Commission of Finnish Power Companies.

Badgley, P.C., 1959. Structural Methods for the Exploration Geologist, Harper and Brothers, New York, pp. 243-254.

Ballou, L., 1979. Field Permeability Measurements, in Waste Isolation Projects: FY 1978, UCLR-50050-78, Lawrence Livermore National Laboratory (Edited by L.D. Ramspott) Jan. 12.

Barker, J.A. and J.H. Black, 1983. Slug tests in fissured aquifers, Water Resour. Res., 19(6), pp. 1558-1564.

Black, J.H., 1985. The interpretation of slug tests in fissured rocks, Q.J. Eng. Geol., London, 18, pp. 161-171.

Bliss, J.C. and K.R. Rushton, 1984. The reliability of packer tests for estimating the hydraulic conductivity of aquifers, Q.J. Eng. Geol., London, 17, pp. 81-91.

Brace, F.W., J.B. Walsh and W.T. Frangos, 1968. Permeability of granite under high pressure, J. Geophys. Res., 73(6), pp. 2225-2236.

Braester, C. and R. Thunvik, 1984. Determination of formation permeability by double-packer tests, J. Hydrol., 72, pp. 375-389.

Bredehoeft, J.D. and S.S. Papadopulos, 1980. A method for determining the hydraulic properties of tight formations, Water Resour. Res., 16(1), pp. 233-238.

Brown, A., 1982. A synopsis of the geology of the URL Site, Proc. of the 12th Infomation Meeting of the Nuclear Fuel Waste Management Program - The Geoscience Program, Atomic Energy of Canada Ltd. Report TR-200, pp. 302-313.

Brown, P.A., D.C. Kamineni, D. Stone and R.H. Thivierge, 1980. General Geology of the Eye-Dashwa Lakes Pluton, Atikokan, Northwestern Ontario, Atomic Energy of Canada Ltd. Report TR-108.

Carlsson, L. and C. Carlstedt, 1977. Estimation of transmissivity and permeability in Swedish bedrock, Nordic Hydrology, 8, pp. 103-116.

Carlsson, A. and T. Olsson, 1977a. Variations of hydraulic conductivity in some Swedish rock types, Rockstore 77 (Stockholm), Vol. 2, pp. 85-91.

Carlsson, A. and T. Olsson, 1977b. Hydraulic properties of Swedish crystalline rocks. The Bulletin of the Geological Institutions of the University of Uppsala, N.S., Vol. 7, prepared by Swedish State Power Board Civil Engineering Development, Uppsala, Sweden, pp. 71-84.

Carlsson, L., G. Gidlund, K. Hansson and C-E. Klockars, 1979. Estimation of hydraulic conductivity in Swedish precambrian crystalline bedrock, OECD-NEA Workshop on Low Flow, Low Permeability Measurements in Largely Impermeable Rocks, Paris, France, pp. 97-116.

Carlsson, A. and T. Olsson, 1982. The storage coefficient of fractured rock determined from deformation tests, Bull. of the Geol. Ins. of the Univ. of Uppsala, (9), pp. 131-136.

Carlsson, A., A. Winberg and B. Grundfelt, 1984a. Hydraulic properties and modelling of potential repository sites in Swedish crystalline rock. IAEA-SR 104, Proc. Seminar on the site investigation techniques and assessment methods for underground disposal of radioactive wastes, IAEA Bulgaria, February 6-10, 1984.

Carlsson, L., A. Windberg and B. Rosander, 1984b. Investigations of hydraulic properties of crystalline rock, in Scientific Basis for Nuclear Waste Management VTT, Symp. Nov., 1983, Boston, Mass. Mat. Res. Soc. Symp. Proc., Vol. 26, pp. 255-267.

Chernis, P.J., 1981. Scanning Electron Microscope Study of the Microcrack Structure of a Granite Semple from Pinawa, Manitoba, Atomic Energy of Canada Ltd. Report TR-173.

Chernis, P.J., 1983. Notes on the Pore-Microfracture Structure of Some Granitic Samples, Atomic Energy of Canada Ltd. Report TR-227.

Chernis, P.J., 1984. Comparison of the Pore-Microcrack Structure of Shallow Deep Samples of the Lac du Bonnet Granite, Atomic Energy of Canada Ltd. Report TR-223.

Cooley, C.H. and S.W. Butters, 1979. Permeability to Water of Granitic Rocks in Support of Canada's Nuclear Waste Isolation Program, Report TR 79-33 prepared for Geological Survey of Canada.

Cooper, H.H., Jr. and J.E. Jacob, 1946. A generalized graphical method for evaluating formation constants and summarizing well-field history, Trans. Am. Geophys. Un. 27(IV), pp. 526-534.

Cooper, H.H., J.D. Bredehoeft and I.S Papadopoulos, 1967. Response of finite-diameter well to an instantaneous charge of water, Water Resour. Res., 7(1), pp. 263-269.

Dagan, G., 1978. A note on packer, slug and recovery tests in unconfined aquifers, Water Resourc. Res., 14(5), pp. 929-934.

Dagan, G., 1979. Models of groundwater flow in statistically homogeneous formations, Water Resour. Res. 15(1), pp.47-63.

Dagan, G., 1981. Analysis of flow through heterogeneous random aquifers by the method of embedding matrix, 1. Steady flow, Water Resour. Res., 17(1), pp. 107-121.

Davison, C.C., 1980. Physical Hydrogeology Methods Conducted in Boreholes WN1, WN2 and WN4 to Assess the Local Hydraulic Conductivity and Hydraulic Potential of a Granitic Rock Mass, WNRE-Report of 1978-1979 Activities, Atomic Energy of Canada Ltd. Report TR-26.

Davison, C.C., 1981. Physical Hydrogeologic Measurements in Fractured Crystalline Rock - Summary of 1979 Research Programs at WNRE and CRNL, Atomic Energy of Canada Ltd. Report TR-161.

Davison, C.C., 1982. Hydrogeological studies at the URL site, Proc. of the 12th Information Meeting of the Nuclear Fuel Waste Management Program - The geoscience program, Atomic Energy of Canada Ltd. Report TR-200, pp.332-353.

Davison, C.C., 1984. Hydrogeological characterization at the site of Canada's Underground Research Laboratory, Proc. International Groundwater Symposium, Montreal, Canada, Vol. II, pp. 310-335.

Davison, C.C., 1985. Hydrogeological characterization of the URL site, Proc. 17th Information Mtg. of the Nuclear Fuel Waste Management Program, Atomic Energy of Canada Ltd. Report TR-299, pp. 231-252.

Davison, C.C., A. Brown and N.M. Soonwala, 1982. Preconstruction site evaluation program at the Canadian Underground Research Laboratory, Proc. of the 14th Information Meeting of the Nuclear Fuel Waste Management Program (1982 General Meeting), Atomic Energy of Canada Ltd. Report TR-207, pp. 162-187.

Davison, C.C. and G.R. Simmons, 1984. The Underground Research Laboratory, Proc. of the 16th Information Meeting of the Nuclear Fuel Waste Management Program (1983 General Meeting), Atomic Energy of Canada Ltd. Report TR-218, pp.74-97.

Doe, T., and J. Remer, 1981. Analysis of constant-head well tests in nonporous fractured rock. 3rd Proceedings - Invitational Well-Testing Symposium, Well Testing in Low Permeability Environments, March 26-28, 1980, Berkeley, CA, CONF-800344, LBL-12076, T.W. Doe and W.J. Schwarz, eds., Earth Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, CA, pp. 84-89.

Drury, M.J., 1981. Thermal Conductivity, Density, Porosity and Mineralogy of Core Samples from Chalk River, Pinawa and Atikokan, Geothermal Service of Canada, Internal Report 81-6.

Earlougher, R.C., Jr., 1977. Advances in well test analysis, Soc. Petro. Eng. AIME Monograph, Vol. 5, Henry L. Doherty Series, New York, 264 pp.

Ershagi, I. and J.J. Woodbury, 1985. Examples of pitfalls in well test analysis, J. Petro. Tech., February, pp. 335-341.

Evans, D.D., 1983. Unsaturated flow and transport through fractured rock - related to high-level waste repositories, NUREG/CR-3206, prepared for the U.S. Nuclear Regulatory Commission by the Department of Hydrology and Water Resoruces, University of Arizona, Tucson, AZ.

Forster, C.B. and J.E. Gale, 1980. A Laboratory Assessment of the Use of Borehole Pressure Transients to Measure the Permeability of Fractured Rock Masses, LBL-8674, SAC-28 Report, prepared for Swedish Nuclear Power Utility Industry and U.S. Department of Energy by University of Waterloo, Canada, and Lawrence Berkeley Laboratory, University of California, Berkeley, CA.

Forster, C.B. and J.E. Gale, 1981a. Injection versus pressure pulse borehole tests in fractured crystalline rock - Observations and recent experience, Proc. 3rd Invitational Well Testing Symposium, Univ. of California, Berkeley, CA., March 26-28, 1980. LBL-12076, pp. 74-83.

Forster, C.B. and J.E. Gale, 1981b. A Field Assessment of the Use of Borehole Pressure Transients to Measure the Permeability of Fractured Rock Masses, LBL-11829, SAC-34.

Fritz, P., 1982. Comments on isotope dating of groundwaters in crystalline rocks, in Geol. Soc. Am. Special Paper 189, Recent Trends in Hydrogeology, ed. T.N. Narasimham, pp. 361-374.

Galbraith, R.M., C.R. Wilson, A.O. Dubois, S.A. Londgren, M.J. McPherson and G.W. West, 1981. Equipment Design, Installation and Operation for the Macropermeability Experiment at Stripa, Sweden, Report LBL-13392, SAC-47, Lawrence Berkeley Laboratory, Berkeley, CA.

Gale, J.E., 1977. A Numerical Field and Laboratory Study of Flow in Rocks with Deformable Fractures. Fisheries and Environment Canada, Inland Waters Directorate, Scientific Series No.72.

Gale, J.E. and K.G. Raven, 1979. An Assessment and Evaluation of Compliance Effects of Borehole Transient Test Equipment, Waterloo Research Institute report, Project No. 901-08 to Environment Canada, 46 p.

Gale, J.E., 1981. Fracture and Hydrology Data from Field Studes at Stripa, Sweden, Report LBL-13101, SAC-46, Lawrence Berkeley Laboratory, Berkeley, CA.

Gale, J.E., A. Rouleau, P.A. Witherspoon and C.R. Wilson, 1982a. Progress with Hydrogeological Characterization of the Stripa Site, LBL-14878, SAC-49, Lawrence Berkeley Laboratory, Berkeley, CA.

Gale, J.E., A. Rouleau and P.A. Witherspoon, 1982b. Hydrogeologic characteristics of a fractured granite, Proc. AWRC Conf, Groundwater in Fractured Rock, Canberra, Australia, August 31-September 3, pp. 95-108.

Gale, J.E., and A. Rouleau, 1983. Characterizing and interpreting the geometry, permeability and porosity of fractures for repository evaluation, Proc. Int. Symp. on Field Measurements in Geomechanics, Zurich, September 5-8, pp. 1343-1369.

Gale, J.E., P.A. Witherspoon, C.R. Wilson and A. Rouleau, 1983. Hydrogeological characterization of the Stripa site, Proc. NEA Workshop on Geol. Disp. Rad. Waste: In situ Experiments in Granite, Stockholm, Sweden, Oct. 25-27, 1982, pp. 79-98.

Gardemeister, R. and P. Rouhiaihen, 1984. Investigations for final disposal of reactor waste at the Loviisa power plant site, Finland, IAEA-SR-104, Sofia, Bulgaria, February 6-10.

Gartner Lee Associates Limited, 1982. Hydrogeological Testing, Forsberg Lake Site, 1981-1982, A report prepared for Atomic Energy of Canada Ltd., 65 p.

Gephart, R.E., S.M. Price, R.L. Jackson and C.W. Meyers, 1984. Geohydrologic factors and current concepts relevant to characterization of a potential nuclear waste repository site in Columbia River Basalt, Hanford Site, Washington, Scientific Basis for Nuclear Waste Management VII, Boston Mtg, pp. 85-94.

Gringarten, A.C. and H.J. Ramey, Jr., 1974. Unsteady-state pressure distributions created by a well with a single horizontal fracture, partial penetration, or restricted entry, Soc. Pet. Eng. J., 14(4), pp.413-426.

Grisak, G.E., J.F. Pickens, D.W. Belanger and J.D. Avis, 1985. Hydrogeologic Testing of Crystalline Rocks During the NAGRA Deep Drilling Program, NAGRA Technischer Bericht 85-08.

GTC Geologic Testing Consultants Ltd., 1986. A Compilation of Subsurface Hydrogeologic Data, reports prepared for Atomic Energy Control Board.

Haimson, B. and T. Doe, 1983. State of stress, permeability, and fractures in the precambrian granite of Northern Illinois, J. Geophy. Res., 88, pp. 355-371.

Harrison, J.E. and R.H. Moench, 1961. Joints in precambrian rocks of the central city-Idaho Springs Area, Colo., U.S. Geol. Survey Prof. Paper 374-B.

Hillary, E., 1982a. Correlation of geological, geophysical and hydrogeological data at the Atikokan research area, Proc. of the 12th Information Meeting of the Nuclear Fuel Waste Management Program - The Geoscience Program, Atomic Energy of Canada Ltd. Report TR-200, pp. 239-262.

Hillary, E., 1982b. Geometrix Representation of Subsurface Fracturing in Boreholes ATK-1, ATK-2, ATK-3, ATK-4, ATK-5, Atikokan, Northwestern Ontario (RA-4), Atomic Energy of Canada Limited Report TR-182.

Hsieh, P.A., S.P. Neuman and E.S. Simpson, 1983. Pressure Testing of Fractured Rocks, A Methodology Employing Three- Dimensional Cross Hole Tests, U.S. Nuclear Regulatory Commission Topical Report NUREG (CR-3213).

Hsieh, P.A. and S.P. Neuman, 1985. Field determination of the three-dimensional hydraulic conductivity tensor of anisotropic media, 1. Theory, Water Resour. Res., 21(11), pp. 1655-1665.

Hsieh, P.A., S.P. Neuman, G.K. Stiles, and E.S. Simpson, 1985. Field Determination of the three-dimensional hydraulic conductivity tensor of anisotropic media, 2. Methodology and application to fractured rocks, Water Resour. Res., 21(11), pp. 1667-1676.

Hult, A., G. Gidlund and U. Thoregren, 1978. Permeability Determination, Geophysical Measurements in Boreholes, KBS-61, Stockholm, Sweden, AECL-TR-MISC-452.

Hutchinson, R.M., 1958. Structure and petrology of the northernmost end of Pikes Peak Batholith, Jefferson and Douglas Counties, Colorado (Abstract), Geol. Soc. Amer. Bull., Vol. 69, p. 1731.

_____, 1959. A^{40}/K^{40} age determinations of rocks associated with north end of Pikes Peak Batholith, Jefferson, Douglas, and Park Counties, Colorado (Abstract), Geol. Soc. Amer. Bull., Vol. 70,p. 1622.

Hutchinson, R.M., 1960. Petrotectonics and petrochemistry of the late precambrian batholiths of Central Texas and north end of Pikes Peak Batholith, Colo., Proc. of the Internatl. Geol. Congress, XXI Session, Part IV, The Granite-Gneiss Problem, pp. 96-107.

_____, 1972. Pikes Peak Batholith and precambrian basement rocks of the Central Colorado Front Range; Their 700-Million Year History, Proc. of the 24th Internatl. Geol. Cong. Section 1, Precambrian Geology, pp. 201-212.

_____, 1976. Precambrian geochronology of the Western and Central Colorado and Southern Wyoming, in Studies in Field Geology, Prof. Contributions of Colo. Sch. of Mines, No. 8, pp. 73-78.

_____, 1983. Geological and Structural Setting of the CSM/OCRD Test Site: CSM Experimental Mine, Idaho Springs, Colorado. BMI/OCRD - 4(2).

Hvorslev, M.J., 1951. Time lag and soil permeability in groundwater observations, Bull. 36, Waterways Experiment Station Corps of Engineers, U.S. Army, Vicksburg, Mississippi.

Isherwood, D., E. Raber and R. Stone, 1981. Site Characterization for Field Radionuclide Migration, UCRL Report 86194.

Jacob, C.E. and S.W. Lohman, 1952. Nonsteady flow to a well of constant drawdown in an extensive aquifer, Trans. Am Geophys. Un., 33(4), pp. 559-569.

Johnson, C.R., R.A. Greenkorn and E.G. Woods, 1966. Pulse testing: A new method for describing reservoir flow properties between wells, J. Pet. Tech., December, pp. 1599-1604.

Jones, J.W., E.S. Simpson, S.P. Neuman and W.S. Keys, 1985. Field and Theoretical Investigations of Fractured Crystalline Rock Near Oracle Arizona, U.S. Nuclear Regulatory Commission Report NUREG/CR-3736.

Laine, T. and H. Tikkanen, 1982. Soil and Bedrock Investigation in Oikiluoto, Report YJT-82-14. Prepared by Saanio and Laine Ltd., Civil and Geological Engineering, Helsinki, Finland, 29 p.

Landstrom, O., C.E. Klockers, K.E. Holmberg and S. Westerberg, 1978. In Situ Experiments on Nuclide Migration in Fractured Crystalline Rocks, KBS-110, Stockholm, Sweden.

Larsson, I., T. Lundgren, U. Wiklander, 1977. Coastal Gneiss in Blekininge, Geology and Hydrogeology, KBS-0025, AECL-TR-MISC-421.

Lee, P.K., K.G. Kennedy and R.E.J. Leech, 1982. Hydrogeologic testing (RA4), Forsberg Lake Site, Atikokan, Northwestern Ontario, Proceedings of the Seventh Nuclear Fueld Waste Management Information Meeting (May 5-6, 1980, Ottawa, Ontario), Atomic Energy of Canada Limited Report TR-190.

Lee, P.K., R. Pearson, R.E.J. Leech and R. Dickin, 1983. Hydraulic testing of deep fractures in the Canadian Shield, Bull. Intern. Assoc. Eng. Geol. No. 26-27, Paris, May 18-20. Symp. Soil and Rock Investigations by In situ Testing, pp. 461-466.

Leech, R.E.J., 1981. Deep borehole testing techniques developed for Canada's Nuclear Fuel Waste Management Program, The Science of the Total Environment, 21, pp. 137-148.

Lindblom, U.E., 1979. Comparison of flow and permeability interpreted from in-situ experiments in granitic rock, Proc. of the Workshop on Low-Flow, Low-Permeability Measurements in Largely Impermeable Rocks, Paris, March 19-21, pp. 125-137.

Louis, C.M., 1969. A Study of Groundwater Flow in Jointed Rock and Its Influence on the Stability of Rock Masses, Imperial College Rock Mechanics Research Report, No. 10, September, London.

Lundstrom, L. and H. Stille, 1978. Large Scale Permeability Test of the Granite in the Stripa Mine and Thermal Conductivity Test. LBL-7052, SAC-02, Report prepared for Swedish Nuclear Power Utility Industry and U.S. Department of Energy by Swedish Nuclear Power Utility Industry and U.S. Department of Energy by Swedish Nuclear Fuel Safety Program.

Maldonado, F., 1977. Summary of the Geology and Physical Properties of the Climax Stock, Nevada Test Site. U.S. Geological Survey, Washington, D.C., Open File Report 77-356.

Marine, I.W., 1966. Hydraulic correlation of fracture zones in buried crystalline rock at the Savannah River Plant near Aiken, South Carolina, Geological Survey Research 1966, U.S. Geol. Surv. Prof. Pap. 550-D, pp. 223-227.

Marine, I.W., 1967. The permeability of fractured crystalline rock at the Savannah River plant near Aiken, South Carolina, U.S. Geological Survey Prof. Paper 575-B, pp. 203-211.

Marine, I.W., 1979. Hydrology of Buried Crystalline Rock at Savannah River Plant near Aiken, South Carolina, U.S. Dept. of Energy Report DOE/SR-WM-79-2.

Marine, I.W., 1981. Comparison of laboratory, in situ and rock mass measurements of the hydraulic conductivity of metamorphic rock at the Savannah River Plant, Water Resour. Res., 17(3), pp. 637-640.

McMullen, E.T. and A.D. Pasternak, 1970. Field Measurements of Fracture Permeability in Granodiorite, UCID-15653, Report prepared for the U.S. Atomic Energy Commission.

Moench, R.H., J.E. Harrison, and P.K. Sims, 1962. Precambrian folding in the Idaho Springs-Central City Area, Front Range, Colorado, Geol. Soc. Amer. Bull., Vol. 73, pp. 35-38.

Montazer P.M. and W.A. Hustrulid 1983. An Investigation of Fracture Permeability Around an Underground Opening in Metamorphic Rocks, BMI OCRD Report 4(5).

Moye, D.G., 1967. Diamond drilling for foundation exploration; Civil Eng. Trans., Inst. Eng. Australia, Vol. CE9, pp. 95-100.

Murray, W.A., 1980. Permeability Testing of Fractures in Climax Stock Granite at the Nevada Test Site, UCRL Report 85231.

Neuman, S.P., and P.A. Witherspoon, 1972. Field determination of the hydraulic properties of leaky multiple aquifer systems, Water Resour. Res., 8(5), pp. 1284-1298.

Neuman, S.P., E.S. Simpson, P.A. Hsieh, J.W. Jones and C.L. Winter, 1985. Statistical analysis of hydraulic test data from fractured crystalline rock near Oracle, Arizona, Proc. Intern. Assoc. Hydrog. Mtg., Hydrogeology of Rocks of Low Permeability, Part 1, pp. 289-300, Tucson, Arizona, Jan. 7-12.

Norton, D., and R. Knapp, 1977. Transport phenomena in hydrothermal systems: The nature of porosity, American Journal of Science, 277, pp. 913-936.

Olkiewicz, A., K. Hansson, K. Almen and G. Gidlund, 1978. Geological and Hydrogeological Basic Documentation of Stripa Experimental Station, KBS Technical Report No. 63 also AECL-TR-MISC-450.

Olkiewicz, A., J.E. Gale, R. Thorpe, and B. Paulsson, 1979. Geology and Fracture System at Stripa, Lawrence Berkeley Lab. Rep. LBL-8907, SAC-21, Berkeley, CA.

Olsson, O. and K. Ahlbom, 1984. Geophysical and geological borehole investigations for the characterization of a site for radioactive waste disposal, IAEA-SR-104, Sofia, Bulgaria, February 6-10, pp. 33.

Pearson, F.J., 1980. Ranges of Selected Geochemical Parameters for use in Risk Assessment Methodology Development, NUREG/CR-1980 SAND81-0557 GF.

Pearson, R., 1982. Research activities in 1982 at Atikokan, Ontario (RA4), Proc. 14th Information Meeting of the Nuclear Fuel Waste Management Program, Atomic Energy of Canada Ltd. Report TR-207, pp. 123-133.

Pearson, R, P. Brown, and N.M Soonawala, 1984. Geoscience research activities in 1983, Proc. of the 16th Information Meeting of the Nuclear Fuel Waste Management Program. (1983 General Meeting), Atomic Energy of Canada Ltd. Report TR-218, pp. 30-50.

Pickens, J.F., D.W. Belanger and G.J. Saulnier, 1985. Analysis of pressure and flow data from the long-term monitoring tool in Bottstein borehole, Nationale Genossenschaft fur die Lagerung radioaktiver Abfalle, Technical Report 85-39.

Pickens, J.F., G.E. Grisak, J.D. Avis and D.W. Belanger, 1986. Analysis and interpretation of borehole hydraulic tests in deep boreholes: principles, model development and applications, Water Resourc. Res. in press.

Pine, R.J., 1983. In-situ hydraulic parameters for the Carnmenellis Granite Hot Dry Rock Geothermal Energy Research Reservoir, Paper presented at the 58th Annual Technical Conference, Soc. Pet. Eng.

Pine, R.J. and A.S. Batchelor, 1984. Downward migration of shearing in jointed rock during hydraulic injections, Int. J. Rock Mech. Min. Sci. and Geomech. Abstr., 21(5), pp. 249-263.

Potter, J.M., 1978. Experimental Permeability Studies at Elevated Temperature and Pressure of Granitic Rocks, Los Alamos Scientific Lab. Thesis LA 7224-t, UC-11, May.

Prats, M. and J.B. Scott, 1975. Effects of wellbore storage on pulse-test pressure response, J. Pet. Tech. Forum, June, pp. 707-709.

Radwan, M.N., 1979. Porosity Measurements by the Immersion Technique for WN-4 and CR-8 Samples, GSC-630049.

Raven, K.G., 1980. Studies in Fracture Hydrology at Chalk River Nuclear Laboratories: 1977/78/79, Atomic Energy of Canada Ltd. Report TR-113.

Raven, K.G., 1982. Geoscience research at the Chalk River Research Area, Proc. 14th Information Meeting of the Nuclear Fuel Waste Management Program, Atomic Energy of Canada Ltd. Report TR-207, pp. 134-142.

Raven, K.G., 1986. Hydraulic Characterization of a Small Groundwater Flow System in Fractured Monzonitic Gneiss, National Hydrology Research Institute NHRI Paper No. 30, IWD Scientific Series No. 149, 133 p.

Raven, K.G. and J.A. Smedley, 1983. CRNL Groundwater Flow Study - Summary of FY 1981 Research Activities, National Hydrology Research Institute Report prepared for Atomic Energy of Canada Ltd.

Raven, K.G. and K.S. Novakowski, 1984. Field investigations of the solute-transport properties of fractures in monzonitic gneiss, Proc. Intern. Groundwater Symp. May, Montreal, Canada, Vol. II, pp. 507-516.

Raven, K.G., J.A. Smedley, R.A. Sweezey and K.S. Novakowski, 1984a. Borehole hydrogeologic investigations at the East Bull Lake Research Area: Summary of 1983 Activities, National Hydrology Research Institute Internal Report to Atomic Energy of Canada Ltd., 91 p.

Raven, K.G., K.S. Novakowski and D.J. Bottomley, 1984b. Hydrogeologic research at the Chalk River Research area, Proc. of the 16th Information Meeting of the Nuclear Fuel Waste Management Program (1983 General Meeting) Atomic Energy of Canada Ltd. Report TR-218.

Raven, K.G., J.A. Smedley, R.A. Sweezey and K.S. Novakowski, 1985a. Field investigations of a small groundwater flow system in fractured monzonitic gneiss, Proc. Intern. Assoc. Hydrog. Meeting, "Hydrogeology of Rocks of Low Permeability", Part 1, pp. 72-86, Tucson, Arizona, Jan. 7-12.

Raven, K.G., J.S.O. Lau, R.B. Ejeckam, J.A. Smedley, R.A. Sweezey and R.J. Sikorsky, 1985b. Borehole geologic and hydrogeologic investigations at the East Bull Lake Research Area, Proc. 17th Information Meeting of the Nuclear Fuel Waste Management Program, Atomic Energy of Canada Ltd. Report TR-299, pp. 200-220.

Raven, R.G., D.J. Bottomley, R.A. Sweezey, J.A. Smedley and T.J. Ruttan, 1986. Hydrogeological characterization of the East Bull Lake Research Area, National Hydrology Research Institute Report to Atomic Energy of Canada Ltd., 141 p.

Rockwell, Hanford Operations, 1982. Site Characterization Report for the Basalt Waste Isolation Project, DOE/RL 82-3, Volume 1.

Rouleau, A., J.E. Gale and J. Baleshta, 1981. Fracture Mapping in the Ventilation Drift at Stripa: Procedures and Results, Lawrence Berkeley Laboratory Report LBL-13071, SAC-42, Berkeley, CA.

Rouleau, A. and J.E. Gale, 1982. Characterization of the Fracture System at Stripa, Lawrence Berkeley Laboratory Report LBL-14875, SAC-52, Berkeley, CA.

Rouleau, A. and J.E. Gale, 1985. Statistical characterization of the fracture system in the Stripa granite, Sweden, Int. J. Rock Mech. Min. Sci. and Geomech. Abstr., 22(6), pp. 353-367.

Sims, P.K., R.H. Moench and J.E. Harrison, 1959. Relation of Front Range mineral belt to ancient precambrian structures (Abstr.), Geol. Soc. Amer. Bull., Vol. 70, p. 1749.

Skagius, K. and I. Neretniks, 1983. Porosities of and diffusivities in crystalline rock and fissure coating materials, Scientific Basis for Nuclear Waste Management VII, G.L. McVay ed. Boston, Ma.

Skagius, K. and I. Neretnieks, 1986. Diffusivity measurements and electrical resistivity measurements in rock samples under mechanical stress, Water Resour. Res., 22(4), pp. 570-580.

Snow, D.T., 1965. A parallel plate model of fracture permeable media, Ph.D. Thesis, University of California, Berkeley.

Snow, D.T., 1979. Packer Injection Test Data from Sites on Fractured Rock, W-7405-ENG-048.

Spane, F.A., Sr. P.D. Thorne, 1985. Effects of drilling fluid invasion on hydraulic characterization of low permeability basalt horizons: A field evaluation, Hydrogeology of Rocks of Low Permeability, Memoires, Volume XVII, Part 1, Proc. Tuscon Meeting, pp. 30-43.

Stone, D., 1980. Distribution of near-vertical surface fractures in the Dashwa pluton, Atikokan, Ontario, Atomic Energy of Canada Ltd. Report TR-125.

Stone, D., 1981. Recent geotechnical work at the Atikokan, Ontario research site, Proc. of the 11th Information Meeting of the Nuclear Fuel Waste Management Program, Atomic Energy of Canada Ltd. Report TR-180, pp. 89-101.

Stone, D., D.C. Kamineni and A. Brown, 1984. Geology and Fracture Characteristics of the Underground Research Laboratory Lease Near Lac du Bonnet, Manitoba, Atomic Energy of Canada Ltd. Report TR-243.

Tammemagi, H.Y. and J.D. Chiesler, 1985. Interim Rock Mass Prop. and Conditions for Analysis of a Repository in Crystalline Rock, BMI/OCRD-18.

Terzaghi, R.D., 1965. Sources of error in joint surveys, Geotechnique, Vol. 15, pp. 287-304.

Thorne, P.D. and F.A. Spane, Jr., 1983. A Comparison of Under-Pressure and Over-Pressure Pulse Tests Conducted in Low-Permeability Basalt Horizons at the Hanford Site, Washington State, Pacific Northwest Laboratories Report PNL-SA-12077.

Thorpe, R., 1979. Characterization of Discontinuities in the Stripa Granite - Time Scale Heater Experiment, Lawrence Berkeley Laboratory Report LBL-7083, SAC-20, Berkeley, CA.

Thorpe, R., D.J. Watkins, W.E. Ralph, R. Hsu and S. Flexser, 1980. Strength and Permeability Tests on Ultra-Large Stripa Granite Core, Report LBL-11203, SAC-31, Lawrence Berkeley Laboratory, Berkeley, CA.

Thorpe, R. and J. Springer, 1981. Fracture Mapping for Radionuclide Migration Studies in the Climax Granite, Lawrence Livermore National Laboratories Report UCID-19081.

Thorpe, R., 1984. An Analysis of Fracturing in Hole UG-2, Spent Fuel Test - Climax, Lawrence Livermore National Laboratory Report UCID 20130.

Van Golf-Racht, T.D., 1982. Fundamentals of Fractured Reservoir Engineering, Elsevier Scientific Publishing Co., New York.

Wadden, M.M., 1979. Porosity Measurements by the Immersion Technique for WN-1, WN-2 and CR-6, 7 Samples, GSC-630079.

Wang, J.S.Y., T.N. Narasimhan, C.F. Tsang and P.A. Witherspoon, 1977. Transient flow in tight fractures, Proc.: First Invitational Well-Testing Symposium, October 19-21, Berkeley, CA, sponsored by USDOE, pp. 103-116.

Webster, D.S. J.F. Proctor and I.W. Marine, 1970. Two-Well Tracer Test in Fractured Crystalline Rock, USGS Water Supply Paper 1544-I.

Weast, R.C., 1984. Handbook of Chemistry and Physics, 64th Edition, CRC Press, Boca Raton, Florida.

Wilder, D.G. and W.C. Patrick, 1980. Geotechnical Status Report for Test Storage of Spent Reactor Fuel in Climax, Granite, Nevada Test Site, UCRL-85096.

Wilder, D.G. and J.L. Yow, Jr., 1984. Structural Geology Report, Spent Fuel Test-Climax, Nevada Test Site, UCRL-53381.

Wilson, C.R., P.A. Witherspoon, J.C.S. Long, R.M. Galbraith, A.O. Dubois, and M.T. McPherson, 1983. Large-scale hydraulic conductivity measurements in fractured granite, Int. J. Rock Mech. Min. Sci. and Geomech. Abstr., 20(6), pp. 269-276.

GLOSSARY OF TERMS

Adsorption	The attachment of an aqueous chemical species to a solid. The attachment may be by an addition or replacment reaction. It may be either physical, designated by a low dependence of the rate of reaction on temperature, or chemical, designated by a high dependence of the rate on temperature.
Advection	To transport solute or energy concurrently with the soil water or groundwater, synonomous with convection.
Anisotropic Medium	A porous medium having directionally dependent properties (e.g., hydraulic conductivity).
Aperture	A measure of the size of opening or silt representative of the void space of a fractured medium.
Aquifer	A formation containing sufficient saturated permeable material to yield significant quantities of water to wells and springs.
Borehole Skin	A term developed in the petroleum literature describing a thin layer of material surrounding a borehole and possessing permeability different than that of the formation.
Brownian Motion	The irregular zigzag movement of extremely minute particles suspended in a liquid.
Capillarity	The property of tubes with hairlike openings when immersed in a fluid to raise (or depress) the fluid in the tubes above (or below) the surface of the fluid in which they are immersed.
Capillary Fringe	The zone immediately above the water table in which water is held above the water table by capillarity.
Compressibility	A material property describing the change in volume or strain induced in a material under an applied stress.
Conduction	Transmission through or by means of a conductor. Distinguished, in the case of energy, from advection and dispersion.
Confined Aquifer	An aquifer bounded above and below by impervious formations.

Consolidation	The process by which the volume occupied by solid porous medium reduces when the effective stress borne by the media increases.
Convection	To transport solute or energy concurrently with the soil water or groundwater, synonomous with advection.
Diffusion	A molecular level process that spreads solute in water as a result of Brownian motion of water molecules.
Dispersion (Mechanical)	Refers to the velocity driven component of hydrodynamic and consists of the product of the groundwater velocity and a coefficient known as dispersivity.
Dispersivity	A coefficient used to relate mechanical dispersion to interstitial groundwater velocity.
Distribution Coefficient	A coefficient representing the partitioning of a groundwater contaminant between liquid and solid phases.
Effective Porosity	The amount of interconnected pore space available for fluid flow expressed as a ratio of interstical volume to total volume, also kinematic porosity.
Equilibrium	The state of a system that is thermodynamically the most stable at a given temperature, pressure, and elemental composition.
Equilibrium Water Saturation	The percent of water filled porosity corresponding to first appearance of a continuous water phase.
Evaporation	The net transfer of water from the liquid phase to the vapour phase.
Evapotranspiration	A combination of the evaporation and transpiration processes.
Fickian Transport or Process	Transport or flux of a solute as a result of Fick's law for molecular diffusion or an analogy applying Fick's law to processes other than diffusion.
Field Capacity	Water content remaining in a unit volume of soil after drainage resulting from gravity, does not represent an intrinsic soil property since gravity drainage continues indefinitely.

Flow Path Tortuosity	The nonstraight nature of soil pores.
Fracture System	A medium where the connected porosity transmitting groundwater is characterized as fractures or fissures.
Free Water Surface	The upper surface of groundwater or that level in the ground where the water is at atmospheric pressure; also water table; also phreatic surface.
Gradient	Change in dependent variable per unit change in spatial or temporal independent variable.
Gravitational Potential	The difference in elevation between the point of interest and a reference point or plane.
Hydration	The process of clustering ions of unlike charge and incorporating water molecules in loosely bound complexes.
Hydraulic Conductivity	The proportionality factor in Darcy's law as applied to the viscous flow of water in soil (i.e., the flux of water per unit gradient of hydraulic potential).
Hydrodynamic Dispersion	The process by which solute spreading occurs on a macroscopic scale due to mechanical and molecular mixing.
Hysteresis	The loop in the moisture content versus matric potential curve defined by the retention (drying) and imbibition (wetting) curves.
Imbibition	To wet or imbibe the soil profile.
Immiscible Displacement	Displacement of one fluid by another.
Infiltration	The downward entry of water into the soil.
Intrinsic Permeability	The property of a rock or soil defining its ability to transmit a fluid.
Ion Exchange	The process of exchanging two ions on an adsorption site.
Isotropic	Independent of direction, used to describe properties of the porous medium (e.g., hydraulic conductivity).

Kinematic Pathline	The path of solute in an aquifer that is determined strictly by the pore water path and velocity.
Kinematic Porosity	The volume of flowing water per unit bulk volume of porous medium, also effective porosity.
Kinetics	A term to designate dynamic chemical changes toward the state of chemical equilibrium.
Mass Flux	Rate of transfer of mass across a surface.
Nonequilibrium	A state of a system that is not thermodynamically the most stable.
Peclet Number	A nondimensional quantity defining the relative importance of advection in comparison to diffusion or diffusion-type dispersion.
Pellicular Water	Water adhering as films to the surfaces of openings and occurring as wedge-shaped bodies at junctures of interstices in the zone of aeration above the capillary fringe.
Permeability	see intrinsic permeability.
Phreatic Aquifer	An aquifer bounded below by an impermeable formation and above by the free water surface.
Pluton	A body of igneous rock that has formed beneath the surface of the earth by consolidation from magma.
Pore	An interstice or void. A space in rock or soil not occupied by solid mineral matter.
Porosity	The ratio of the volume of voids to the total volume of porous media.
Porous Media, Medium	A physical environment containing voids, pores, interstices, or other openings that may or may not interconnect.
Potentiometric Head	The height of a surface to which water in an aquifer would rise by hydrostatic pressure.
Reactive Solute	A solute that reacts with the medium by any of a number of processes.
Recharge	The quantity of water or the process by which water is added to the zone of saturation.

Relative Saturation	The ratio of water-filled pore volume to total pore volume.
Retardation Factor	The reciprocal of the retarded solute velocity of the groundwater (i.e., reciprocal of relative velocity).
Saturation (water)	The total water that can be absorbed by water-bearing materials without dilation of the sediments.
Soil Matrix	The unconsolidated mineral material comprising a major portion of, if not the entire, vadose zone.
Soil Water Potential	The amount of work a unit quantity of water in an equilibrium soil-water system is capable of doing when it moves to a pool of water in the reference state of the same temperature.
Solute	The chemical species appearing as a dissolved constituent in soil water or groundwater.
Specific Retention	The volume of water per unit area of soil retained by a soil column.
Specific Storage	The volume of water that a unit volume of a formation releases from storage due to a unit decline in head.
Specific Yield	The volume of water per unit area of soil released by a soil column, extending from land surface to free water surface, when the water table is lowered one unit depth.
Storativity	The volume of water that a unit area of an aquifer releases from storage for a unit decline in head.
Thermal expansivity	A material property describing the volumetric change resulting from changes in temperature.
Transmissivity	The flow of water through a unit width of aquifer under a hydraulic gradient of one equal to the product of hydraulic conductivity and aquifer thickness (for a saturated confined aquifer).
Transpiration	The process by which plants remove moisture from the soil and release it to the atmosphere as vapour.

Unsaturated System	That portion of the subsurface geology where the porosity is shared by water and air, and the matric potential is nonzero (i.e., the water content of the soil profile is less than saturation).
Vadose Water	Water in excess of pellicular water seeping toward the water table; used in this text as a synonym for gravity water.
Viscosity, Coefficient of	The amount of force necessary to maintain a unit difference in velocity between two layers of water a unit distance apart.
Void Ratio	Ratio of void volume to solid volume.
Water Table	In pervious granular material the water table is the upper surface of the body of free water which completely fills all openings in material sufficiently pervious to permit percolation. In fractured impervious rocks and in solution openings it is the surface at the contact between the water body in the openings and the overlying ground air.